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Water Quality and Hydrological Benefits of a Natural Treatment System in an Urban Watershed in Southern California

Jamie L. Burkhard,^{1*} Karina K. Johnston,² Jose A. Saez,³ and John H. Dorsey³

¹*West Basin Municipal Water District, Carson, CA 90746*

²*Marine Science Institute, University of California Santa Barbara,
Santa Barbara, CA 93106*

³*Loyola Marymount University, Los Angeles, California 90045*

Abstract.—Bioretention systems are important tools for capturing and infiltrating polluted runoff, but more data are needed on their effectiveness within Mediterranean climates. A two-year study investigated water retention and pollutant loading in the Ballona Creek Rain Garden during 28 storms. This system was constructed to infiltrate runoff from light industrial and commercial operations bordering the Creek. Study goals were to measure flows and pollutant concentrations in runoff entering and leaving the garden and integrate these to calculate mass loading. Nine pollutants were measured at all flowing inlets/outlets two to three times per storm. Infiltration rates ranged from 18% to 100% and averaged 74% across 28 storms. Average pollutant retention across all nine pollutants for all nine sampled storms was 71.6%. Results demonstrate that bioretention systems can be effectively used in urban Mediterranean climates to promote infiltration, capture pollutants, and prevent polluted stormwater from reaching impaired water bodies.

Stormwater runoff along with its associated pollutants and impacts to recreational water bodies has long been a predominant water quality issue worldwide. Impervious surfaces that constitute vast areas within urbanized watersheds reduce infiltration, resulting in high volumes of polluted runoff washing directly into waterways during storms with few opportunities for treatment. Traditional challenges in stormwater management can be further influenced and exacerbated by regionally-specific weather patterns. In Mediterranean climates, summers are dry and hot, and winters are mild and rainy (Lionello et al. 2006). In these types of climates, storm intensity, duration, and frequency are all subject to higher future variability in the face of climate change. Swain et al. (2018) projected that California may experience “climate whiplash” where drought conditions can rapidly transition to extremely wet weather. For example, during the 2003–04 winter season, Los Angeles recorded a total of 23.5 cm of rainfall, which was 14.1 cm below the seasonal average of 36.8 cm. Total precipitation quadrupled the following season to 94.6 cm during an El Niño event.¹ Southern California and other locations with Mediterranean climates undergo months without any precipitation, allowing pollutants to accumulate on the land surface before being flushed into waterways. This circumstance result in the seasonal first flush phenomenon (Stenstrom and Kayhanian 2005), where the initial stormwater flow of the season carries the highest pollutant concentrations relative to subsequent storm events. Thus, potential changes to wet weather events due to climate variability in combination with urban impervious surfaces increase the potential loading of stormwater

* Corresponding author: Jamie.Burkhard@gmail.com

¹ Los Angeles Almanac. 2021. Total seasonal rainfall (precipitation). <http://www.laalmanac.com/weather/we13.php>, 26 September 2024.

pollutants within these systems. This highly polluted runoff can impact ecological functions in freshwater and marine habitats, as well as human health of people exposed to these constituents.

Low Impact Development (LID) strategies have increasingly been applied in recent years throughout urban areas to address stormwater flooding and pollution issues. LID systems represent a wide variety of systems for green infrastructure highlighting sustainable methodology and nature-based projects. These strategies focus on shifting current hydrologic processes to mimic natural or pre-development versions (Zhan and Chui 2016). LID strategies offer a wide range of practices with multiple environmental, social, and financial benefits. Rather than promoting a single solution, LID systems offer a toolkit that can be adapted to different locations, site sizes, costs, and implementation and technical feasibility. As such, LID strategies are emerging as promising solutions to drastically improve urban waterways and mitigate the effects of urban stormwater runoff (Ambrose and Winfrey 2015). This trend reflects a divergence with historical stormwater management approaches that focused on flood control and abatement using hardscapes (Ahiablame et al. 2012; Dietz and Clausen 2006).

Bioretention systems are a subset of LID structures that capture and infiltrate runoff through some combination of vegetation and soil media without the use of an underdrain (LARWQCB 2012). These nature-based systems also promote a variety of ecosystem services that are particularly valuable in urban areas by enhancing biodiversity while benefiting communities socially and economically (Elmqvist et al. 2016; Reid et al. 2005; Abbott et al. 2016). Green spaces like rain gardens offer places for recreation and social interaction, promote relaxation (Jabbar et al. 2022) and enhance native biodiversity. Within a system, captured runoff undergoes sedimentation, filtration of particles, and pollutant sorption to finer particles (Hatt et al. 2009). Nutrient uptake and cycling also occur alongside degradation of organic matter and sequestration of metals. Bioretention systems are becoming increasingly popular for several reasons such as aesthetic enhancements, small energy footprints, and design flexibility (Ambrose and Winfrey 2015). In addition to urban runoff decontamination, stormwater infiltration can bolster groundwater aquifers to augment an area's drinking water supply and provide many other ecosystem services making urban habitats more sustainable (Elderbrock et al. 2020; Elmqvist et al. 2016).

A variety of studies across multiple regions and climatic conditions have confirmed the services that these systems provide, including water retention and associated pollutant reductions. Several studies from the U.S. East Coast found retention of heavy metals including copper, lead, and zinc above 80% at many sites (Davis et al. 2003; Dietz and Clausen 2006; Roseen et al. 2006; Hunt et al. 2008). Other studies from Australia and New Zealand demonstrated substantial peak flow attenuation and high retention rates for heavy metals and sediments (Hatt et al. 2009; Trowsdale and Simcock 2011; Al-Ameri et al. 2018). Solids, nutrients, metals, and organics were reduced during a five-year study in Korea (Jeon et al. 2021).

Using bioretention systems in cities with Mediterranean climates like Los Angeles is far less studied but constitutes a great opportunity for improving water quality of receiving waters (Ambrose and Winfrey 2015). Multiple agencies from public and private sectors are working to construct LID systems throughout southern California. Although LID systems have gained popularity, there is little quantitative information about their effectiveness.

Ballona Creek Watershed.—The Ballona Creek Watershed, located in southern California, includes all or portions of the following municipalities: Beverly Hills, Culver City, Inglewood, Santa Monica, West Hollywood, as well as portions of the City and County of Los Angeles (Fig. 1). The watershed area encompasses $\sim 337 \text{ km}^2$ (130 mi^2), with about 63.7% residential, 19.6% commercial, light industrial, and other unknown land uses, and 16.7% open space

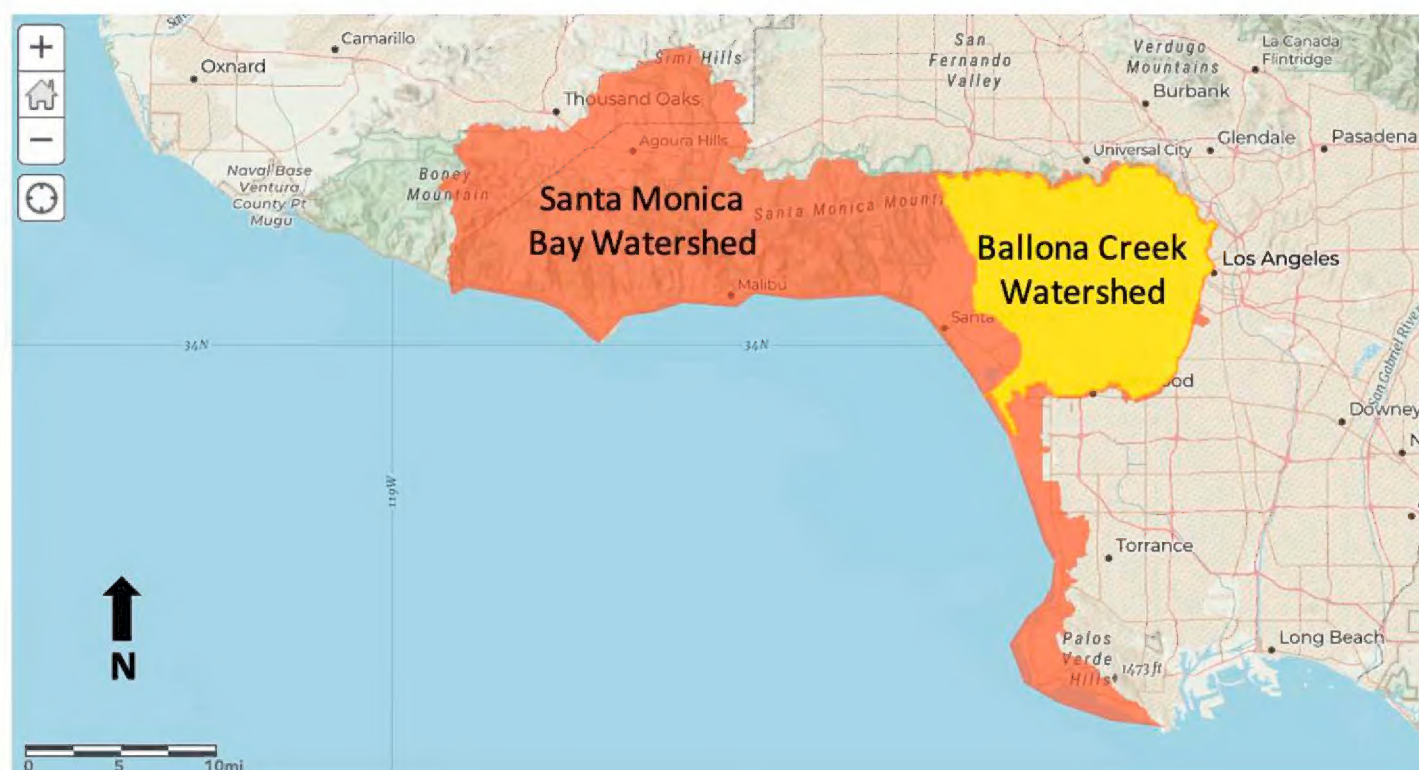


Fig. 1. Location of the Ballona Creek Watershed within the Santa Monica Bay region of southern California.

(LACFCD 2015). It is the largest single watershed draining to the Santa Monica Bay (Dojiri et al. 2003). This degree of urbanization coupled with an extensive concrete-lined storm-drain system results in an increase of polluted wet- and dry-weather runoff impacting water quality in Santa Monica Bay² (Bay et al. 2003, Dojiri et al. 2003). Contaminants in the runoff can include trash, surfactants, pesticides, herbicides, fertilizers, trace metals, synthetic organic chemicals, petroleum products, sediment, and fecal bacteria that periodically result in public beach closures (Washburn et al. 2003). The focus of this study was on metals, organics, and bacteria.

Runoff in the watershed runs through an extensive storm drain system, eventually entering Ballona Creek, an open, 14.2 km (8.8 mi) concrete-lined channel. Prior to flowing into Santa Monica Bay, the Creek channel transitions into a 4.7 km long estuary whose banks are concreted, but whose bottom comprises sediments (City of Los Angeles 2018). Flows of runoff in the Creek are highly variable. Data from 1987-2012 for Ballona Creek at Sawtelle Station from the Los Angeles Regional Water Quality Control Board (2013) indicated that the average daily flows ranged from 0.03 - 148 cm/s with a median flow of 0.5 cm/s; weather flows are categorized as those above 1.8 cm/s.

Ballona Creek Rain Garden.—The Bay Foundation (TBF), a non-profit environmental organization based in Los Angeles, acquired funding to construct a bioswale, also known as a rain garden, on either side of Ballona Creek in Culver City, California to reduce the load of pollutants reaching the Creek and Santa Monica Bay (Fig. 2). A residential rain garden of approximately 100 m in length and widths varying between 3-6 m was installed on the west bank of the creek, receiving runoff from the adjacent residential neighborhood. A second larger rain garden of approximately 300 m in length and widths varying between 6-8 m was constructed on the east bank, receiving runoff from a commercial and industrial area. One of the main goals of the project was to “capture, treat and infiltrate all runoff from a 1-inch (25.4 mm) storm in the Residential bioswale and 0.75-inch (19.1 mm) storm in the Commercial/Industrial bioswale” (Abramson 2014). All work for this study occurred at the eastern

² Heal the Bay (2024). 2023-2024 Beach Report Card.

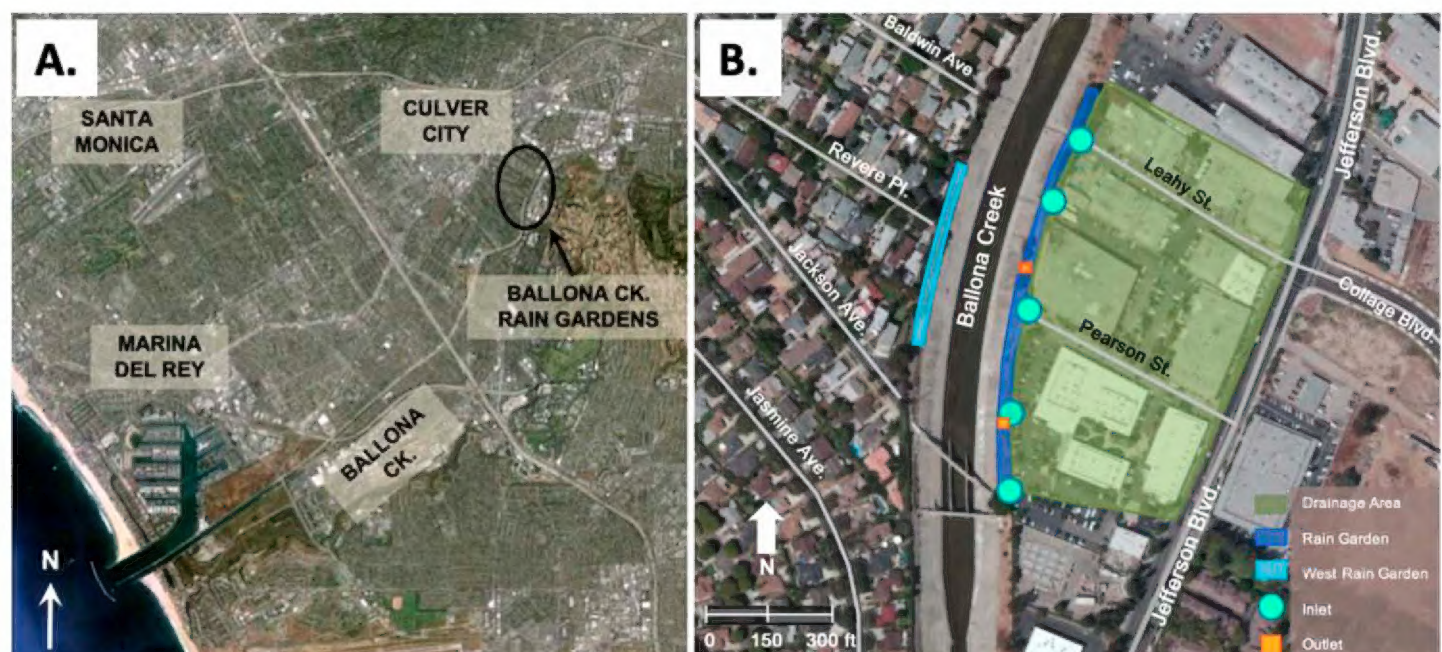


Fig. 2. Location of the Ballona Creek Rain Gardens in Culver City, California: A) Location of the gardens relative to Marina del Rey; B) Position of the commercial garden (study site) along the east bank of Ballona Creek where runoff is received from industrial and commercial operations. The West Rain Garden shown in light blue was not included in this study.

bioswale receiving runoff from the commercial and industrial areas and will herein be referred to as the Ballona Creek Rain Garden (BCRG).

The BCRG was constructed in 2011 with additional enhancements made in March 2014 to increase its retention capacity (Abramson 2014). The BCRG receives runoff from approximately 4.57 ha of surrounding commercial and industrial properties (Fig. 2). The basic design included removal of the top foot of soil, recontouring the sediments into a swale, and subsequently amending the native soil (a sandy loam) with 50% mature, vegetative waste compost down to a 2 m depth. The design also included installing cobble and boulders to slow stormwater flow. Drought-tolerant native plants provide aesthetic value, surface area for pollutant capture, as well as native habitat for wildlife and other ecosystem services (e.g., biodiversity, carbon sequestration, nutrient uptake, and water purification) (Prudencio and Null 2018; Potschin et al. 2016). An engineered reinforcement structure and a decomposed granite path along the Creek-side edge allows access along the site (Abramson 2014). Runoff from a small tributary urban watershed enters the BCRG via five inlets, is screened through grates and slowed in the garden to maximize infiltration. Once the BCRG reaches maximum capacity, ponding runoff enters two outlet structures and overflows by gravity into Ballona Creek where it mixes with creek flows, entering Santa Monica Bay 8.8 km downstream (Fig. 3).

Los Angeles County's normal seasonal precipitation is 38.2 cm and the 85th percentile, 24 hr design storm for the BCRG is 2.8 cm.^{3,4} The site was designed to capture and treat storms up to 1.9 cm, with excess flows directed into the creek. The 85th percentile design storm is a commonly used metric for hydrology and water quality analyses based on research showing that these smaller but more frequent storms often contain the greatest pollutant volume (California State Water Resources Control Board 2018).

³ Los Angeles County Public Works, Alert system for real-time precipitation data. [Gage Alert ID 370]. <http://dpw.lacounty.gov/wrd/Precip/alertlist.cfm>, 26 September 2024.

⁴ Los Angeles County Public Works, Stormwater Engineering Division, Hydrologic Records. 2020. Precipitation information page, Ballona Creek @ Sawtelle Blvd. <https://dpw.lacounty.gov/wrd/rainfall/>, 26 September 2024.

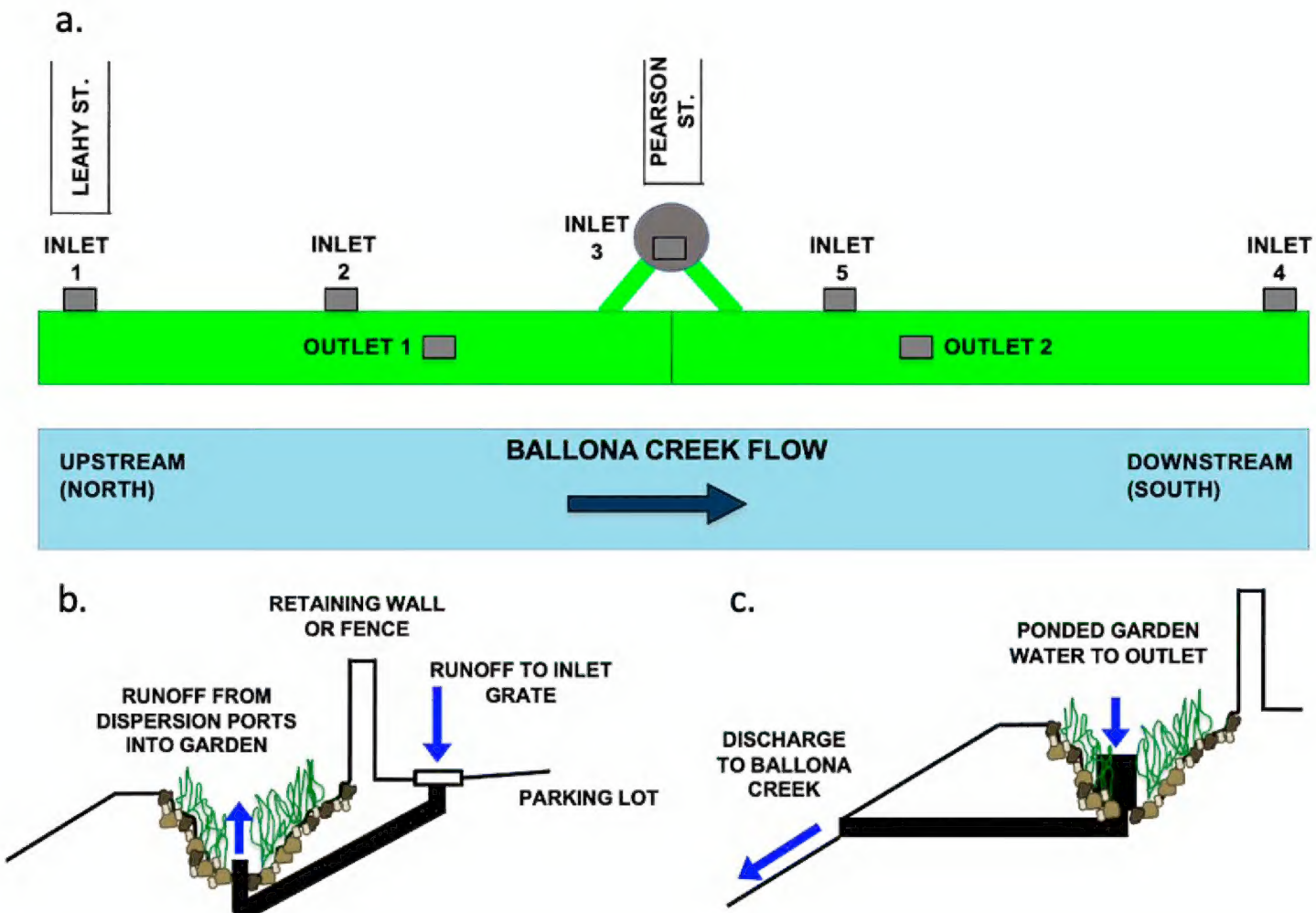


Fig. 3. Garden configuration showing: a) five inlets and two outlet structures that redirect flow into Ballona Creek when at full capacity; b) cross sectional view of the general inlet design; and c) cross sectional view of the outlet design.

After the original installation and the enhancements in 2014, TBF performed monitoring work to assess performance. Total metals, hardness, total suspended solids (TSS), total petroleum hydrocarbons (TPH) from diesel and gasoline, and fecal indicator bacteria (FIB) were sampled for three storm events. There was a decrease in pollutant concentrations across all constituents, with higher reductions identified for FIB and TSS (Abramson 2014). Specific pollutants were chosen because of historical exceedances and total maximum daily loads (TMDLs).

Study goals and research questions.—Building on the preliminary work of Abramson (2014), the goal of this study was to obtain more precise and quantitative loading information on the effectiveness of the BCRG in infiltrating storm runoff and sequestering (removing) associated pollutants from the waters entering Ballona Creek. Specific study questions included the following:

1. What was the water retention capacity for this rain garden and how did it compare to that of the upstream watershed tributary to the BCRG?
2. What was the pollutant retention efficiency across a variety of pollutants for this rain garden? Retention is defined here as the mass of pollutants removed from storm runoff discharged into Ballona Creek due to rain garden processes.
3. Did the size of the storm (volume, duration, or intensity) affect either runoff infiltration or pollutant retention within the garden?

The general approach in addressing these questions was to quantify the volume of water and mass loading of pollutants entering and exiting the garden into Ballona Creek during storms. This information can provide essential evidence about the efficacy of rain gardens



Fig. 4. Inlet weir 3 during dry and wet weather conditions.

in Mediterranean climates and help assess their value as a potential LID tool in these regions.

Materials and Methods

This study took place at the BCRG in 2016 and 2017. All storms were monitored for flow rate. Storms that were targeted for water quality sampling included those that generated runoff in the watershed tributary to the BCRG inlets, but not necessarily at the outlets from the BCRG to Ballona Creek. For each storm, the goal was to capture three sets of samples reflecting the rise, peak, and fall of runoff flows at the BCRG inlets and outlets; two sets of samples were obtained if the storm moved through the area too quickly to capture a third sample.

During the first and second seasons, four and five storms, respectively, were monitored for both flow rate and pollutant concentrations. To provide additional information regarding water infiltration during the second season, all storms forecasted to have greater than 0.25 cm (0.10 in) of rainfall were measured for flow rate. Over the two seasons, flow measurements were acquired for 28 storm events and pollutant concentrations were measured during nine of these storms.

Flow monitoring.—To calculate runoff flows entering and exiting the BCRG, seven weirs were individually designed and constructed for each of the five inlet and two outlet structures. The weirs were sharp-crested and of the compound type. Each weir was comprised of a 90° V-notch for lower flow rates and a suppressed rectangular section for higher flow rates. Water flowed over the weirs by gravity and under free-flow, open channel conditions. Fig. 4 shows a photo of Inlet Weir 3 during dry and flowing conditions.

HOBO units (Onset Co. Model No. U20L-04) were deployed in each weir prior to storm events to record temperature and pressure measurements during the storm at 1 min intervals for up to 15 d. Each of the inlet and outlet weirs contained a HOBO unit placed within a perforated PVC pipe in the weir forebay at the recommended distance upstream of the weir notch at a set elevation to ensure accuracy in the readings. The HOBO units recorded pressure and temperature upstream of the V-notch. One unit, placed at Inlet 3 out of reach of water, captured ambient temperature and air pressure readings. Once the storm passed, the sensors were retrieved, and data were downloaded using Onset HOBOWare Pro software. After adjusting water pressure by subtracting the ambient atmospheric pressure, the resulting pressure readings were converted into equivalent water heights (head) using the procedure described by McCutcheon et al. (1993).

Based on weir dimensions and head (H measured in meters) relative to the weir notch (Fig. 5), flow rate (Q_V measured in liters per min) was calculated using Equation 1 (Grant and Dawson 1995). The equation selected one of two subequations depending on the magnitude of

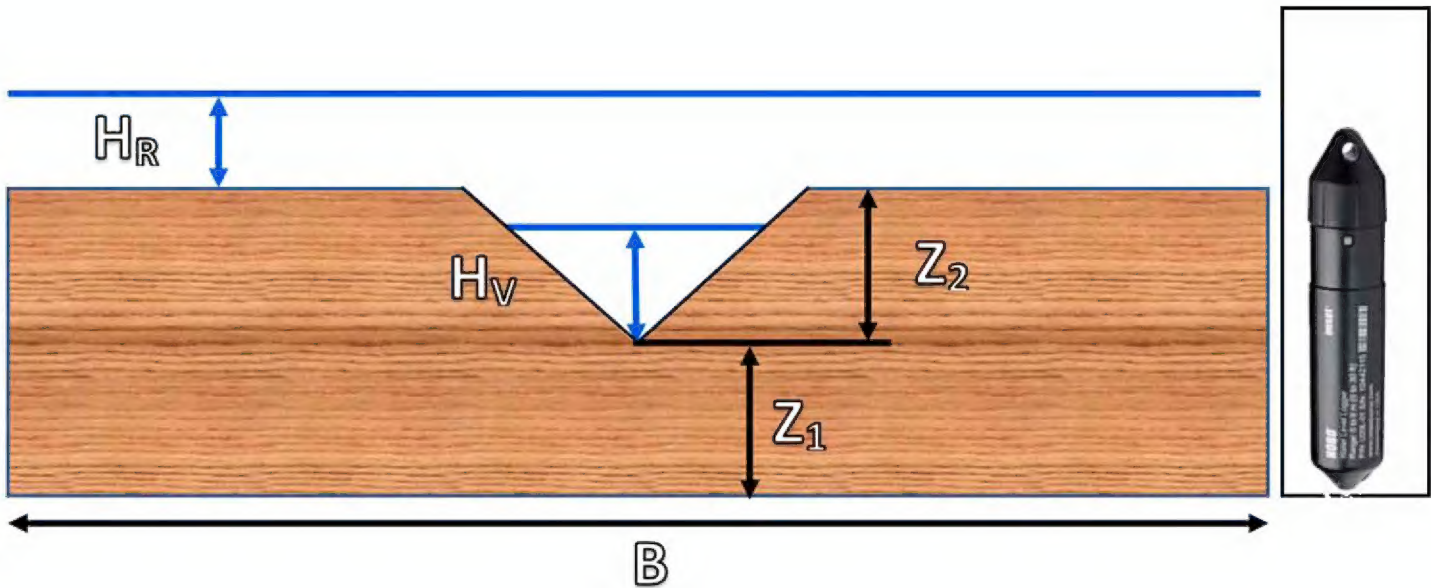


Fig. 5. Weir dimensions for flow cales and an image of a HOBO unit used in this study.

head value (H) relative to weir dimension Z_2 . Equation 1a is applied when H is greater than Z_2 . Equation 1b is applied when H is less than Z_2 . In essence, 1b is used when the triangular weir handles the entire flow at lower heads, while 1a is used when the flow is split into the triangular and rectangular weirs at higher heads. Flows from all inlets were then added at each time segment to yield a total inflow, and the same was done for outlet flows.

$$Q_v = 82800 H_v^{2.5} + 110400 B H_R^{1.5} \text{ (valid for } H > Z_2, \text{ then } H_v = Z_2 \text{ and } H_R = H - Z_2)$$

(Equation 1a)

$$Q_v = 82800 H_v^{2.5} \text{ (valid for } H = H_v < Z_2 \text{ or } H = H_v = Z_2)$$

(Equation 1b)

Hydrographs and hyetographs.—Table 1 shows the parameters and dimensions that were used in Equation 1 to determine the flow rate in each weir. Inflow and outflow over time were plotted to create a hydrograph for each storm at the BCRG showing the flow rate (Q) over time (t) at 1 min intervals. The Los Angeles County Public Works (LACDPW 2004) Water Resources Division continuously measures rainfall intensities at an automatic recording gage along Ballona Creek at Sawtelle Boulevard positioned approximately 1.9 km downstream and southwest of the BCRG. This station provided total rainfall as well as rainfall intensities at 5 min intervals for all 28 storms. The station was assumed to provide representative data of the rainfall in the small urban watershed tributary to the BCRG. The resulting rainfall data were used to determine total precipitation and to develop hyetographs for each storm showing rainfall intensity over the storm duration.

Table 1. Key dimensions for each weir to determine flow rates using Equation 1.

Weir location	B (m)	Z ₁ (m)	Z ₂ (m)
Inlet 1	0.572	0.025	0.074
Inlet 2	0.572	0.072	0.074
Inlet 3	0.572	0.017	0.051
Inlet 4	0.457	0.159	0.105
Inlet 5	0.622	0.159	0.105
Outlet 1	0.813	0.254	0.105
Outlet 2	0.813	0.152	0.105

Water infiltration.—The BCRG was treated as a single system for this study. Infiltration data were calculated by comparing BCRG's total inflow and total outflow volumes regardless of specific inlet or outlet flow due to garden construction limitations. Using the volume reduction from Gulliver et al. (2010) with Equation 2, percent infiltration was calculated (Note: similar equations are used to calculate other percent reductions, such as the percent reduction in peak flow rate).

$$\% \text{ Infiltration} = [(\text{Volume}_{\text{inflow}} - \text{Volume}_{\text{outflow}}) \div \text{Volume}_{\text{inflow}}] \times 100\% \quad (\text{Equation 2})$$

Multiple linear regression analyses were performed using data from the 28 storms measured to determine if any of the three independent variables associated with storms [rainfall intensity (mm/min), duration of storm event (min), and total rainfall (mm)] substantially affected the volume (L) of runoff infiltrated in the BCRG or the percent infiltration (R Studio Ver. 2021.09.1; R Core Team 2021). Four multiple linear regression models were run for each of the dependent variables and Akaike information criterion (AIC) was used to select the best fit model. Single linear models were also evaluated for several individual variables. The garden design was intended to infiltrate quickly to prevent standing surface water. Hence, evaporation effects of water in the BCRG were disregarded, as across the storm durations, it is likely that they were negligible or minor in comparison to infiltration. As such, infiltration was calculated by subtracting outflow from inflow. When no outflow was recorded, the BCRG was assumed to have infiltrated 100% of the associated runoff.

Storm runoff coefficients in the watershed tributary to the BCRG.—A comparison was made for each storm between the estimated total volume of rainfall that fell on the urbanized subwatershed that contributes the only water input to the BCRG and the volume of direct runoff it produced. This comparison allowed for the assessment of the watershed's runoff potential and impervious characteristics, which were later compared with those of the BCRG. Equation 3 uses the drainage area of approximately 4.57 ha, which was measured using drainage and satellite maps, as well as the recorded rainfall depth and appropriate unit conversions to calculate rainfall volume.

$$\text{Rainfall Volume (L)} = (4.57 \text{ ha}) \times \text{Total Rainfall (mm)} \times \left(\frac{10^4 \text{ L}}{\text{ha} \times \text{mm}} \right) \quad (\text{Equation 3})$$

The volume of direct runoff was obtained by subtracting baseflow from the total hydrograph which the inlet weirs produced (i.e., inflow to the BCRG). The variability of rainfall within storm events often produced hydrographs with several peaks and extended tails in the receding limb. Volume calculations required careful baseflow volume separation through a combination of typical techniques and best professional judgment to calculate the volume of direct runoff. Equation 4 was then used to determine the unitless ratio (coefficient) $\hat{C}$ relating the two volumes described.

$$\hat{C} = \text{Volume}_{\text{direct runoff}} \div \text{Volume}_{\text{total rainfall}} \quad (\text{Equation 4})$$

$\hat{C}$ represents an average runoff coefficient over the entire storm event (i.e., the portion of rainfall that becomes runoff). It is similar to the runoff coefficient (C) commonly used in Hydrology's Rational Method (Kuichling and Hering 1889). A minor difference between the $\hat{C}$ and C coefficients is that the former was determined in this study as an average value over

the storm event, while the latter is mostly applied to instantaneous flow conditions (e.g., at peak flow rate). A second difference, which this work partially addresses, is that the $\hat{C}$ coefficient may vary with total rainfall, antecedent conditions and other factors associated with the storm event. $\hat{C}$ and C values are positive and range from values slightly above zero in pervious watersheds to values near one in impervious drainage areas. The calculated $\hat{C}$ values helped characterize the watershed's imperviousness and compare it with the higher infiltration benefit that the BCRG provides to the same watershed. The calculated $\hat{C}$ values were also used to qualitatively assess the weir flow monitoring data. The calculated C values corresponded to a relatively impervious area. Because the watershed tributary to the BCRG was relatively impervious, this suggested that the flow monitoring data were reasonably accurate. Lastly, Equation 4 can be rearranged to determine volume infiltrated and percent infiltration in the upstream watershed through Equations 5 and 6.

$$\text{Volume}_{\text{Infiltrated in Watershed}} = (1 - \hat{C}) \times \text{Volume}_{\text{Rainfall}} \quad (\text{Equation 5})$$

$$\% \text{ Infiltration in Watershed} = (\text{Volume}_{\text{Infiltrated in upstream Watershed}}) \div (\text{Volume}_{\text{Rainfall}}) \quad (\text{Equation 6})$$

Pollutant concentrations and mass loading.—Target storms for sampling were tracked using radar images available from the National Weather Service (L.A./Oxnard Office). Using radar, the intensity and speed of a storm was determined to deploy crews to collect samples during the rise, peak, and fall of an event. Samples were collected at each inlet and outlet (if flowing) by filling each sample container with flowing runoff as it passed into the weir. Sets of samples were returned to the lab between sampling runs to begin analyses for contaminants like bacteria with short holding times. In general, concentrations of pollutants were measured following Standard Methods (APHA 2005). Limited grab samples per storm event may result in errors in estimating loading for individual storm events (Leecaster et al. 2002); however, sampling effort was limited by factors including storm duration, size, and resources for sample analyses. Pollutants measured included: fecal indicator bacteria (FIB: *Escherichia coli*, enterococci), total suspended solids (TSS), copper, zinc, lead, polyaromatic hydrocarbons, diesel hydrocarbons, and gas hydrocarbons.

Three replicate samples ($n = 3$) for fecal indicator bacteria were collected during each sampling run in sterile 125 mL polypropylene containers from each flowing inlet and outlet, placed on ice, and processed within 2 hr of collection time. Concentrations (Most Probable Number/100 mL) were determined using chromogenic substrate tests (APHA 1998; Standard Methods Section 9223 for *E. coli* and 9230 for Enterococci). IDEXX media Colilert[®]-18 was used to measure Most Probable Number (MPN) of *E. coli* while Enterolert[®] was used for enterococci (IDEXX Laboratories, Inc., Westbrook, ME). Each sample was diluted to 0.01 (1 mL of sample into 99 mL of sterile, dilution water) and quantified using IDEXX Quanti-Tray[®] 2000 97-well trays. Lab blank controls were included with each collected batch of samples to confirm sterility of the dilution water.

From each flowing inlet and outlet, 1 L of runoff was collected in a polypropylene container to measure concentrations (mg/L) of total suspended solids using the gravimetric procedure described in APHA (2005; Standard Methods 2540D). Within 1 hr of collection, up to 1 L of runoff was filtered depending on the concentration of TSS. Samples with elevated TSS resulted in less water being filtered due to clogging of the glass filters; whereas, the entire 1 L sample was filtered for other samples. The filters were then dried and weighed to quantify the solids present in the volume of liquid filtered per sample.

Runoff samples for metal analyses (copper, zinc, and lead) were collected in Corning® 50 mL self-standing centrifuge tubes. Hydrochloric acid (HCl) was added to each vial after returning to the lab to acidify samples (pH <2.0). Samples were later processed using inductively coupled plasma-mass spectrometry (ICP/MS) according to the procedure given in United States Environmental Protection Agency (USEPA 1997; Method 1640). The organic compounds (polyaromatic hydrocarbons, diesel hydrocarbons, gas hydrocarbons) were collected in 1.0 L amber glass jars, refrigerated, and then transported on ice to the Institute for Integrated Research in Materials, Environments, and Society (IIRMES) laboratory located at California State University, Long Beach. Concentrations of the polyaromatic, diesel, and gas hydrocarbons were determined using EPA Method 8015 (USEPA 2000).

Several metals and organics concentration results fell below equipment method detection levels. These data presented a challenge when trying to combine with uncensored data or to use them in the mass loading calculations described above. To more properly account for these non-detects (NDs) and detected-not-quantified (DNQs) values, consistent rules were applied to all data before completing mass loading calculations. For all organics' concentrations in the DNQ range falling between the reporting limit (RL) and minimum detection level (MDL), the measured concentration was reported and used for calculations without any adjustments. For metals concentrations falling below the MDL, a value of half the MDL was used in calculations. This approach is common when dealing with DNQ values in data analyses (Cao et al. 2017). Where no information about RLs or MDLs existed for metals concentrations, any negative concentration results were replaced with the smallest positive concentration for the inlet or outlet for the specified metal.

Pollutant mass loading and retention estimates.—The summation of load method (Gulliver et al. 2010) was used to generate mass loading for each pollutant entering and exiting the BCRG by multiplying the discharge volume of water by the corresponding mean concentration of the pollutant during the specific storm segments of the hydrograph. Fig. 6 displays how each segment was determined by identifying its midpoint between sampling times for the rise, peak, and falling portions of the hydrograph. For example, the rising segment in Fig. 6 would range from time t_0 to a point midway between t_1 and t_2 . Loading estimates were made for the rise, peak, and fall of the longer storms, but only for the rise and fall for the shorter events. It was assumed that the grab samples collected represented average pollutant concentrations at rise, peak, and fall segments within storms, and that the timing of the sampling runs corresponded to these segments.

Using Equation set 1, 1 min interval values were obtained for the total inlet or outlet flow, Q_v . By using Equation 7, a total volume per time segment of the storm (V_i) was obtained using the Q_v value and the trapezoidal rule (Weir et al. 2010). The limits of the integral were chosen to assure that the grab sample times were the actual midpoint times for the rise and peak segments.

$$V_i = \int_{m_i}^{m_{i+1}} Q_v(t) dt \quad (\text{Equation 7})$$

V_i = Discharge volume for storm segment i

$i = 1$ (Rise), 2 (Peak), 3 (Fall)

m_i = integral limits = $\{0, \frac{t_{s1} + t_{s2}}{2}, \frac{t_{s2} + t_{s3}}{2}, t_{\text{final}}\}$

t_{s1}, t_{s2}, t_{s3} = grab sample times

$Q_v(t)$ = flow rate (L/min).

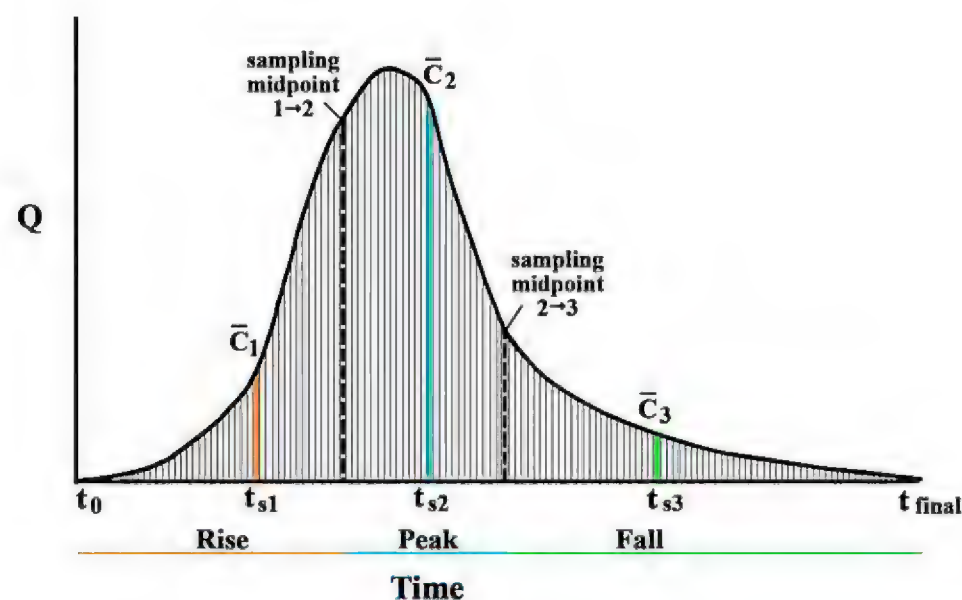


Fig. 6. Hydrograph integration of flow and concentration.

Pollutant concentrations were averaged across all flowing inlets and outlets for the rise, peak, and/or falling segments of each storm and assumed to represent average conditions at all inlets and outlets for the specified time segment. The mean pollutant concentration was integrated with flow data to estimate the mass of pollutants entering and exiting the BCRG. Mass loads (M) were calculated by multiplying mean pollutant concentrations (C_i) and volumes in each time segment (V_i) for the rise, peak, and fall of the storm for all inlets and all outlets, and by integrating them over each runoff event (Equation 8 and as seen in Fig. 6).

$$M = \sum_{i=1}^3 \bar{C}_i V_i \quad (\text{Equation 8})$$

M = Total mass loading of pollutant

$i = 1$ (Rise), 2 (Peak), 3 (Fall)

V_i = Discharge volume for corresponding hydrograph segment

$\bar{C}_i$ = Mean pollutant concentration among inlets or outlets.

The percent retention (PR) within the BCRG for each pollutant was then calculated by comparing mass loads entering and departing the BCRG as shown in Equation 9.

$$\text{Percent Retention (PR)} = \left(1 - \frac{M_O}{M_I} \right) \times 100\% \quad (\text{Equation 9})$$

M_O = Total mass load from outlets

M_I = Total mass load from inlets.

Results

Rainfall characterization.—Twenty-eight storms were measured for flow rate during the study period of which nine storms were sampled for pollutants. The average rainfall duration

Table 2. Summary data for all events surveyed for hydrology across the two-year study.

Storm date	Rainfall period (hr)	Rainfall total (mm)	Mean intensity (mm/hr)	Total rainfall volume (L)	Inlet volume*	Outlet volume**	Volume infiltrated in BCRG (L)	Percent infiltrated in BCRG (%)	Inlet peak flow rate (L/min)	Outlet peak flow rate (L/min)	Percent peak reduction at BCRG (%)
Fully infiltrated storms											
26-Nov-16	1.7	5.1	3.05	232,306	137,219	–	137,219	100.0%	4,651	–	100.0%
30-Dec-16	18.1	6.1	0.34	278,767	181,874	–	181,874	100.0%	1,399	–	100.0%
31-Dec-16	3.4	1.5	0.45	69,692	72,933	–	72,933	100.0%	1,139	–	100.0%
7-Jan-17	2.8	1.8	0.63	81,307	70,003	–	70,003	100.0%	723	–	100.0%
3-Feb-17	11.4	5.3	0.47	243,921	208,451	–	208,451	100.0%	1,309	–	100.0%
7-8 Feb-17	10.0	1.5	0.15	69,692	53,637	–	53,637	100.0%	310	–	100.0%
19-20-Feb-17	9.0	1.3	0.14	58,076	48,607	–	48,607	100.0%	331	–	100.0%
21-Feb-17	1.3	1.0	0.81	46,461	32,633	–	32,633	100.0%	976	–	100.0%
26-Feb-17	2.8	1.3	0.45	58,076	31,313	–	31,313	100.0%	352	–	100.0%
21-22 Mar-17	15.0	3.0	0.20	139,383	127,084	–	127,084	100.0%	1,721	–	100.0%
Storms > 85% and Seasonal First Flush											
5-Jan-16 (s)	7.3	34.8	4.80	1,591,294	1,294,781	512,072	782,709	60.5%	21,731	16,769	22.8%
5-7 Mar-16 (s)	36.3	28.2	0.78	1,289,297	1,163,547	335,601	827,946	71.2%	16,487	3,373	79.5%
20-21 Nov-16 (s)	15.7	16.0	1.02	731,763	682,174	175,822	506,352	74.2%	7,226	1,750	75.8%
15-16 Dec-16 (s)	14.7	37.8	2.58	1,730,678	1,440,005	845,652	594,353	41.3%	16,372	11,593	29.2%
22-23 Jan-17	24.6	57.7	2.35	2,636,670	2,135,766	1,743,552	392,214	18.4%	15,762	12,126	23.1%
17-18 Feb-17 (s)	24.8	39.6	1.60	1,811,985	1,515,903	1,020,103	495,800	32.7%	9,310	6,441	30.8%
Storms from 6.2 mm to <85%, except seasonal first flush											
31-Jan-16 (s)	6.1	6.1	1.00	278,767	160,806	15,665	145,141	90.3%	2,842	471	83.4%
11-Mar-16 (s)	1.9	11.2	5.83	511,073	450,448	151,812	298,636	66.3%	19,101	3,214	83.2%
21-22 Dec-16	22.0	16.3	0.74	743,378	537,307	93,927	443,380	82.5%	6,565	1,423	78.3%
4-5 Jan-17 (s)	11.6	10.9	0.94	499,457	360,461	38,303	322,158	89.4%	2,152	642	70.2%
9-Jan-17	5.9	21.3	3.61	975,684	623,565	370,586	252,979	40.6%	11,338	5,089	55.1%
10-11 Jan-17	22.8	6.1	0.27	278,767	262,018	37,743	224,275	85.6%	3,640	923	74.6%

Table 2. Continued.

Storm date	Rainfall period (hr)	Rainfall total (mm)	Mean intensity (mm/hr)	Total rainfall volume (L)	Inlet volume*	Outlet volume**	Volume infiltrated in BCRG (L)	Percent infiltrated in BCRG (%)	Inlet peak flow rate (L/min)	Outlet peak flow rate (L/min)	Percent peak reduction at BCRG (%)
11-12 Jan-17	16.9	26.7	1.58	1,219,605	858,408	612,345	246,063	28.7%	16,000	9,332	41.7%
19-Jan-17 (s)	4.8	19.3	4.06	882,762	751,230	505,962	245,268	32.6%	6,737	5,538	17.8%
20-Jan-17	10.3	25.4	2.46	1,161,529	979,478	709,035	270,443	27.6%	9,503	8,355	12.1%
6-Feb-17	12.3	19.6	1.60	894,377	810,639	388,603	422,036	52.1%	4,100	1,961	52.2%
7-Feb-17	9.4	9.1	0.97	418,150	279,141	26,921	252,220	90.4%	1,600	327	79.6%
10-11 Feb-17	14.8	9.9	0.67	452,996	297,351	9,088	288,263	96.9%	1,747	147	91.6%
Total	337.5	423.9		1,94E+07	1.56E+07	7.59E+06	7.97E+06				
Average	12.1	15.1	1.55	6.92E+05	5.56E+05	2.71E+05	2.85E+05	74.3%	6612	3196	71.5%
Maximum	36.3	57.7	5.83	2.64E+06	2.14E+06	1.74E+06	8.28E+05	100.0%	21731	16769	100.0%
Minimum	1.3	1.0	0.14	4.65E+04	3.13E+04	0	3.13E+04	18.4%	310	0	12.1%
Standard Error	1.6	2.7	0.29	1.25E+05	1.03E+05	7.80E+04	4.01E+04	5.4%	1251	864	5.8%

(s) Storms sampled for pollutants.
* Runoff Volume from Upstream Watershed to Inlets (L).
** Runoff Volume to Ballona Creek (L).

was 12.1 hr from first to last recorded rainfall, with the shortest at 1.3 hr and the longest lasting 36.3 hr (Table 2). Total rainfall per event averaged 15.1 mm, ranging from 1.0 to 57.7 mm. Mean intensity averaged 1.55 mm/hr with a range from 0.14 mm/hr to 5.83 mm/hr. Lastly, the rainfall volume, calculated using Equation 3, averaged 6.92×10^5 L with a range of 4.65×10^4 L to 2.64×10^6 L. Table 2 shows all storms categorized by total rainfall. There are fully infiltrated storms, storms meeting the seasonal first flush or 85th percentile design criteria, and storms that fall between these two criteria.

BCRG infiltration.—As hypothesized, the BCRG's inlet and outlet volumes increased with higher total rainfall (Table 2). The difference between these two volumes was used to determine the infiltration volume at the BCRG. The volume infiltrated in the garden was highly variable, ranging from 3.13×10^4 L on 26 February 2017, during one of the smallest storms to 8.28×10^5 L on 5–6 March 2016, during the longest storm of the study. Percent infiltration of the runoff entering the BCRG ranged from 18.4% to 100%, averaging 74.3%. Thus, an average of 25.7% of the inflow to the BCRG resulted in excess runoff to Ballona Creek.

One hundred percent of the rainfall was infiltrated across 10 storms (36% of the measured storms), with total rainfall determined to be 6.1 mm or less. Table 2 shows that these fully infiltrated storms resulted in lower volumes infiltrated with no runoff flowing to Ballona Creek. Larger storms often resulted in lower infiltration percentages, higher infiltration volume and higher runoff volume to the creek. An increase in total rainfall appeared to be a major reason for higher infiltration volumes in the BCRG, but higher variability and exceptions were noticed in a few of the moderate and large storm events. For example, during the largest storm of the sampling period (22–23 January 2017) where 57.7 mm fell over 24.6 hr, 18.4% or 3.92×10^5 L of runoff infiltrated within the garden (Table 2). Later that season, 32.7% or 4.96×10^5 L infiltrated during a slightly smaller storm of similar duration (17–18 February 2017; 39.6 mm of total rainfall over 24.75 hr). It is probable that this apparent discrepancy in infiltrated volume may be due to a difference in antecedent conditions before each storm and in saturation levels within the garden. The first (larger) storm was preceded by two storms with above average magnitudes two and three days earlier, respectively. These preceding storms may have contributed to partial or full saturation of the BCRG and less infiltration. Conversely, runoff from the second (smaller) storm, which was preceded 6 d prior by a storm with a magnitude significantly below the average, may have acted on drier conditions within the garden, thus enhancing filtration and reducing excess runoff to the creek. A second possible reason for the apparent discrepancy may be due to the larger storm's higher peak flow rates, which almost doubled the peak flow rates in the smaller storm and may have reduced the garden's ability to infiltrate the incoming runoff.

Results from the multiple linear regression analyses indicated that both the volume infiltrated (L) and percent infiltration (dependent variables, run separately) were strongly influenced by both storm duration (hr) and total rainfall (mm). Results indicate that the volume of runoff infiltration increased with increasing rainfall, while the percent infiltration decreased as total rainfall increased. This consequence was expected, because the percent infiltration was hypothesized to decrease as volumes from larger storms increase due to the capacity of the rain garden (Fig. 7). Fig. 7 displays the data and best fit lines for total rainfall, which was found to be one of the driving variables influencing both percent infiltration and volume infiltrated.

The best fit multiple linear regression analysis for volume infiltrated (L) as the dependent variable included storm duration (hr) and total rainfall (mm) as the selected independent variables. Results of the analyses identified a close positive relationship between percent infiltration and the independent variables (Multiple linear regression, $F = 31.78$, $p < 0.001$, $\text{Adj } R^2 = 0.695$).

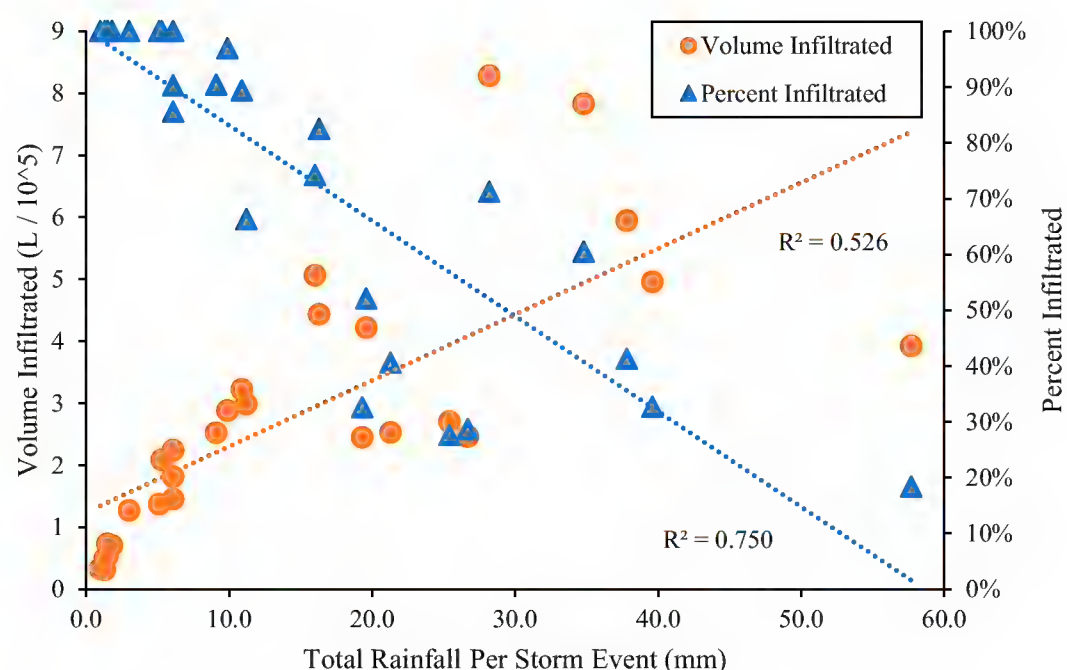


Fig. 7. Relationship between total infiltration and percent infiltration per storm as a function of total rainfall.

The best fit multiple linear regression analysis for percent infiltration as the dependent variable included total rainfall (mm) and intensity (mm/hr) as the selected independent variables. Results of the analyses identified a close negative relationship between percent infiltration and the independent variables (Multiple linear regression, $F = 73.85$, $p < 0.001$, $\text{Adj } R^2 = 0.844$). The selected variables explained approximately 84% of the variation in the dependent variable. Additional statistical analyses are available in Appendix 2.

Hydrographs and hyetographs.—Hydrographs were generated by using the pressure data collected from the HOBO units installed at the weirs (all hydrographs available upon request). Fig. 8 presents a representative hydrograph and corresponding hyetograph for a larger storm event on 6 February 2017, where total rainfall measured 19.6 mm. During this storm several peak flows measured early for the inlet weirs resulted in zero flow at the outlet weirs. This circumstance indicated that 100% of the corresponding inlet volume infiltrated into the BCRG during the first 2 to 3 mm of measured rainfall and was typical of storms with rainfall of 6.1 mm or less. As rainfall increased, the BCRG infiltrated a considerable portion of the inlet volume, while runoff rapidly increased at the outlet weirs to Ballona Creek. As rainfall subsided, the outlet flows gradually decreased and remained at zero during a final small inflow peak 4 hr later, indicating that the BCRG was able to infiltrate 100% of the remaining inflow runoff. The multiple peaks in the inlet and outlet hydrographs followed the pattern of the hyetographs with expected lagging and reduction in peak flows and the typical dispersion behavior. This pattern was especially evident when outlet flows appeared during the second half of the storm.

Hydrologic characteristics of urban watershed upstream of the BCRG (Baseline condition).—The volumes and peak flow rates at the inlet weirs to the BCRG represent the hydrologic conditions of the upstream subwatershed without the garden. The drainage area was ideal in terms of scale, because its relatively small size prevented the generation of excessively high peak flow rates that could have exceeded the hydraulic capacities of the flow monitoring measuring weirs. The baseline conditions can be compared to those of the BCRG to assess the garden's hydrologic benefits. Appendix 1 shows the runoff coefficients ($\hat{C}$) for each storm. The $\hat{C}$ coefficients averaged 0.76 and ranged from 0.54 to

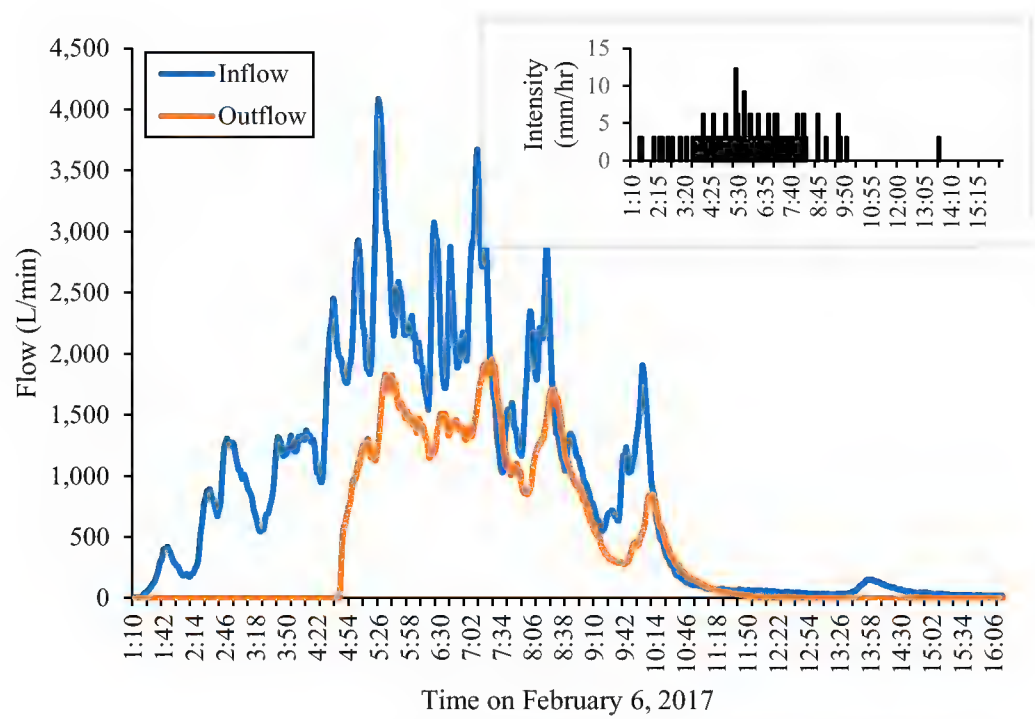


Fig. 8. Storm hydrograph and embedded hyetograph for 6 February 2017. The blue line shows the combined inflow from all inlets and the orange line shows the combined outflow.

0.93, notwithstanding one outlier value of 1.00 for a small storm (1.5 mm of rainfall on 31 December 2016). The runoff coefficients are reasonable as the small urban watershed, which is mostly composed of commercial and light industrial parcels, is relatively impervious and should result in runoff coefficients within this range. The range of values of the runoff coefficients also suggested that the flow monitoring data were reasonably accurate as they reflected the relatively high imperviousness of the urban watershed.

The total infiltration volume for the 28 storms was 7.97×10^6 L in the BCRG, almost twice the total infiltration volume of 4.03×10^6 L in the upstream watershed (Table 2, Appendix 1). Fig. 9 shows that as total rainfall increased, infiltration volume increased in the BCRG (Single Linear Regression, $F = 28.84$, $p < 0.001$, $R^2 = 0.526$), as had been shown in Fig. 7, and this also occurred in the upstream watershed (Single Linear Regression, $F = 91.31$, $p < 0.001$, $R^2 = 0.770$). The vertical difference between the two trendlines and between the total infiltration volumes in Table 2 and Appendix 1 indicate that

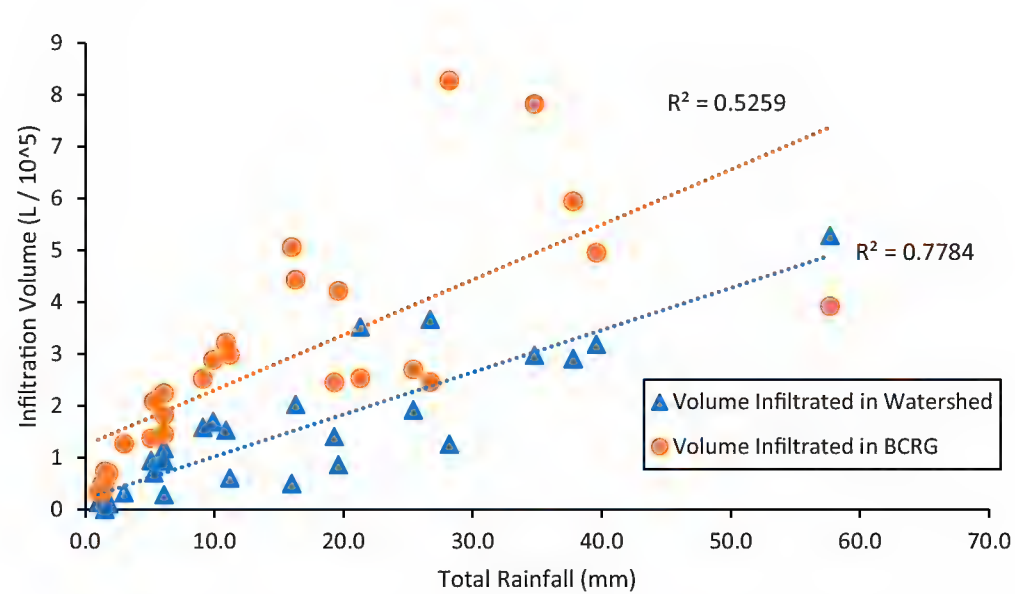


Fig. 9. Comparison of infiltration volumes in BCRG and upstream watershed vs. total rainfall.

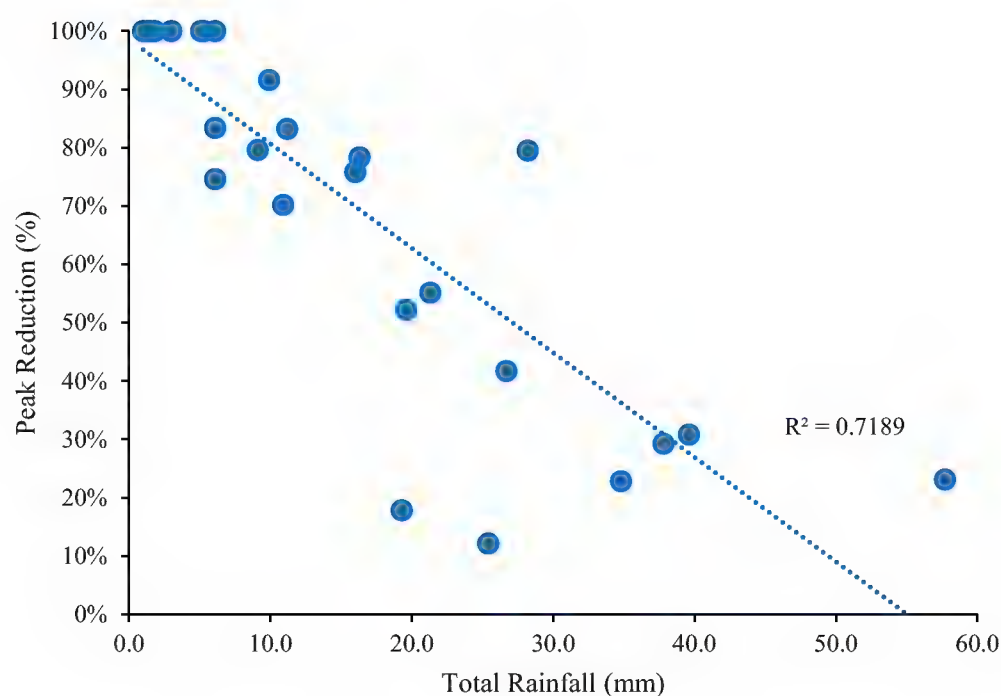


Fig. 10. Reduction in peak flow rate in BCRG vs. total rainfall.

the BCRG infiltrated well in excess of 10^5 L more than the watershed per storm event (1.41×10^5 L). The larger data scatter in the BCRG may be due to storage effects, antecedent conditions, and other variables (e.g., lower infiltration occurring at the garden when the storm is closely preceded by other storm events). The same reasons may explain the three instances when the volume infiltrated in the upstream watershed exceeded those in the BCRG during a heavy rain period in January 2017 (9, 11–12, and 22–23 January 2017). In addition, the BCRG reduced the total runoff volume from the measured watershed to Ballona Creek by 51.4% across the 28 storms studied (1.56×10^7 L total inlet runoff volume into the garden vs. 7.59×10^6 L total runoff volume to the creek). Lastly, the combination of the BCRG with the upstream watershed resulted in an equivalent runoff coefficient of 0.39, which is approximately half of the average value (0.76) obtained for the upstream watershed and is comparable to those found in much less urbanized areas.

Fig. 10 depicts substantial decreases in the peak flow reduction through the BCRG. The garden achieved an average percent reduction of the peak flow rate equal to 71.5% with a highly variable range (12.1% to 100%) (Table 2). Fig. 10 plots the percent reduction in instantaneous peak flow rate through the BCRG as a function of total rainfall for all 28 storms. The graph illustrates a negative relationship between total rainfall (independent variable, mm) and peak reduction percentage (Single Linear Regression, $F = 66.49$, $p < 0.001$, $R^2 = 0.719$) with considerable scatter, which was likely due to storage effects and antecedent conditions in the garden. Nevertheless, Fig. 10 shows that the BCRG achieved the highest reductions of peak flow rates at lower total rainfall levels. This is further evidence of the BCRG's ability to infiltrate the runoff and reduce peak flow rates at perfect efficiency (100%) for storms below 6.1 mm, while providing substantial reductions for larger storm events.

Water quality.—Pollutant concentrations were variable across individual storm events as well as time periods within the storms. Among the nine sampled storms, the average inlet concentrations generally were greater than average outlet concentrations for all pollutants (Tables 3–5; raw data available upon request). However, there were 15 instances

Table 3. Mean concentrations of fecal indicator bacteria (*E. coli*, Enterococci) and total suspended solids (TSS) at inlets and outlets during each storm.

Storm date	<i>E. coli</i> (MPN/100 ml)						Enterococci (MPN/100 ml)						TSS (mg/L)			
	Inlet			Outlet			Inlet			Outlet			Inlet		Outlet	
	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	SE
1/5/16*	36	3258	753	12	581	81	36	9200	1796	12	7528	1002	12	12.23	3.08	24.38
1/31/16	21	2280	641	3	3510	273	24	12998	2171	3	7390	1274	3	1.58	0.56	0.8
3/5/16*	21	7257	1873	12	5117	678	21	7012	1286	12	6721	1005	7	0.83	0.45	0.65
3/11/16	24	4647	1590	6	237	44	24	5276	1136	6	6885	1052	8	7.13	2.72	6.95
11/20/16*	24	2418	382	3	16877	177	24	7376	1212	3	32143	5888	8	9.28	4.15	1.54
12/15/16*	42	7486	2262	6	4952	186	42	7377	2507	6	6862	1765	14	23.77	6.06	0.49
1/5/17	24	633	108	3	223	87	24	2883	864	3	2967	177	8	17.69	5.89	2.21
1/19/17	30	637	142	9	511	109	30	1899	511	9	3858	522	10	7.58	1.67	2.21
2/17/17*	39	2131	403	6	5762	1579	39	6583	1151	6	8008	682	13	26.67	13.63	2.36

N = number of samples.
SE = Standard error.
* Storms meeting 85% design or seasonal first flush criteria.

of higher average outlet concentrations out of 78 total occurrences (<20%). Of these instances, eight of the 15 elevated outlet concentrations were for concentrations of fecal indicator bacteria (Table 3). Bacterial counts tended to display high variation as seen in Table 3. In one example, 5–6 March 2016, the lowest *E. coli* concentration was 200 MPN/100 mL, peaking at 32,550 per 100 mL later in the storm.

Among metals, zinc had the highest average inlet concentrations per storm with mean concentrations ranging from 23.7 ug/L to 493.7 ug/L. Lead had the lowest (means ranged from 0.05 ug/L to 18.4 ug/L) while copper fell in the middle (means ranged from 2.6 ug/L to 68.2 ug/L) (Table 4). When averaged over the entire storm, all metals had lower outlet concentrations compared to inlet concentrations (Table 4).

Concentrations of both diesel and motor oil hydrocarbons were similar while polyaromatic hydrocarbons had generally much lower concentrations (Table 5). The maximum mean inlet concentrations for these organics were 49.0 ug/L for PAHS, 847.1 ug/L for diesel, and 380.0 ug/L for motor oil (Table 5). Like the other pollutants measured, the hydrocarbons tended to have reduced concentrations in water flowing from the outlets, although on two occasions for both PAHs and diesel hydrocarbons, and once for motor oil, the average outlet values for were higher. As expected, Tables 3-5 show that pollutant concentrations were generally higher for the 85 percentile and seasonal first flush storm events.

Similar to the concentrations, high variability was observed for mass loading estimates of pollutants, especially for the bacteria (Table 6). Enterococci had higher mean mass loadings for both inlets and outlets compared to *E. coli*, but the average percent mass retention within the garden was higher for *E. coli* (52.9% for *E. coli* vs. 47.7% for Enterococci across all nine storms). Enterococci had the lowest average mass percent retention within the garden for all nine pollutants. An average of nearly 80% of the suspended solids mass was retained in the garden; although, in some instances loading of TSS discharged to the creek was greater than entering the garden. The mass of zinc entering the garden surpassed the other metals by a substantial margin (average value of 193.6 g versus averages of 21.0 g and 5.0 g for copper and lead, respectively). Despite the difference in mass, metal results showed similar high average percent retention loadings, at 80.6% for copper, 76.5 for zinc, and 76.4% for lead. Mass loading trends for organics were similar to concentration trends, with PAHs again being much lower than both diesel and motor oil mass inputs. Motor oil hydrocarbons showed high input masses at an average of 182.1 g, and they experienced the highest retention within the garden at an average of 84.2%. Collectively, the grand mean overall pollutant retention within the garden across the nine storms for all nine pollutants was 71.6%.

Discussion

The BCRG performed well six years after its original construction by meeting its original goals of reducing pollutant loading to Ballona Creek. Data from this study indicated that the system was capable of retaining large amounts of urban stormwater and its associated pollutants and presumably also can capture and retain dry weather runoff. In particular, the system was highly effective at capturing and retaining water and pollutants during smaller storm events.

A key question for this study was how effectively runoff was infiltrated into the BCRG relative to runoff retention in the upstream watershed. The BCRG achieved significant

Table 4. Mean concentrations of metals at inlets and outlets during each storm.

Storm date	Copper (µ/L)						Zinc (µ/L)						Lead (µ/L)					
	Inlet			Outlet			Inlet			Outlet			Inlet			Outlet		
	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE
1/5/16*	12	3.67	0.49	4	2.52	0.55	12	24.35	3.74	4	8.79	1.52	12	0.51	0.11	4	0.17	0.11
1/31/16	8	2.63	0.27	1	1.72	—	8	23.72	3.42	1	8.93	—	8	0.05	0.01	1	0.02	—
3/5/16*	7	3.05	0.46	4	1.25	0.06	7	45.77	7.79	4	21.1	2.4	7	0.06	0.03	4	0.06	0.01
3/11/16	8	19.64	4.04	2	15.98	5.71	8	249.9	56.73	2	158.94	10.94	8	4.37	1.42	2	2.14	1.73
11/20/16*	8	60.19	5.9	1	55.8	—	8	472.3	47.95	1	444.08	—	8	18.25	6.08	1	12.44	—
12/15/16*	14	68.24	9.61	2	27.85	4.06	14	459.3	38.11	2	196.74	2.55	14	18.37	2.45	2	11.69	5.82
1/5/17	8	38.27	5.44	1	18.32	—	8	493.7	50.37	1	320.25	—	8	9.31	2.46	1	5.92	—
1/19/17	10	11.96	7.22	3	5.1	0.71	10	144.7	20.15	3	115.79	6.4	10	0.97	0.16	3	0.73	0.11
2/17/17*	13	13.59	3.52	2	5.01	1.95	13	190.4	22.64	2	163.32	31.58	13	1.7	0.52	2	1.22	0.64

n = number of samples.
SE = Standard error.
* Storms meeting 85% design or seasonal first flush criteria.

Table 5. Mean concentrations of organic hydrocarbons at inlets and outlets during each storm.

Storm date	Polyaromatic hydrocarbons (µ/L)						Diesel hydrocarbons (µ/L)						Motor oil hydrocarbons (µ/L)					
	Inlet			Outlet			Inlet			Outlet			Inlet			Outlet		
	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE	n	Mean	SE
1/5/16*	12	14.94	2.71	4	13.35	5.92	12	106.00	16.52	4	84.88	13.85	12	10.61	1.82	4	4.50	1.50
1/31/16	6	8.33	2.08	1	18.67	—	6	847.10	750.80	1	110.70	—	6	32.80	18.64	1	2.70	—
3/5/16*	7	2.73	0.86	4	7.33	2.12	7	116.20	27.18	4	58.78	5.98	7	115.70	49.41	4	170.90	71.47
3/11/16	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
11/20/16*	7	16.26	4.89	1	5.73	—	7	83.23	5.67	1	98.70	—	7	380.00	107.30	1	81.50	—
12/15/16*	14	49.03	8.78	2	10.39	5.23	14	80.35	14.19	2	51.15	26.05	14	318.80	62.59	2	100.10	42.20
1/5/17	8	9.10	1.75	1	1.57	—	8	87.58	10.19	1	37.70	—	8	248.30	60.11	1	44.40	—
1/19/17	10	4.44	0.91	3	2.49	1.05	10	43.50	3.84	3	46.83	9.34	10	89.97	12.48	3	62.57	9.51
2/17/17*	13	21.56	9.88	2	3.04	0.76	13	205.20	57.47	2	104.10	82.20	13	329.00	121.70	2	82.05	35.15

n = number of samples.
SE = Standard error.
nd = no data.
* Storms meeting 85% design or seasonal first flush criteria.

Table 6. Mean mass loading among all storms for inlets and outlets.

Pollutant	n	Inlets		Outlets		Retained		% Retention			
		Mean	SE	Mean	SE	Mean	SE	Mean	SE	Min	Max
<i>E. coli</i> (MPN × 10 ⁹)	9	35.4	12.7	15.2	6.5	20.3	10.6	52.9	20.3	-78.5	98.4
Enterococci (MPN × 10 ⁹)	9	58.9	14.7	29.0	8.3	29.9	10.7	47.7	14.9	-31.0	93.5
Total Suspended Solids (kg)	9	11.7	4.4	2.8	2.2	8.9	4.4	76.6	11.4	-7.8	98.8
Copper (g)	9	21.0	9.3	5.1	2.6	15.8	6.7	80.6	3.3	70.6	94.7
Zinc (g)	9	193.6	68.9	54.2	20.6	139.4	51.6	76.5	6.2	44.4	96.2
Lead (g)	9	5.0	2.7	1.8	1.3	3.2	1.5	76.4	5.9	51.5	96.5
Total PAHs (g)	8	16.3	7.1	2.6	1.0	13.6	6.3	77.0	6.1	51.8	98.1
Diesel hydrocarbons (g)	8	125.9	33.5	28.6	10.2	97.3	28.8	72.7	7.7	31.9	99.2
Motor oil hydrocarbons (g)	8	182.1	62.3	27.2	10.3	154.9	53.5	84.2	5.1	54.4	99.4

n = number of samples.
SE = Standard error.

reductions of peak flow rates with runoff volumes reduced, on average, by 74% to the creek. For ten storms (<6.1 mm), all runoff was infiltrated. As such, the BCRG provided increased hydrologic benefits to the watershed’s overall ability to infiltrate runoff. This assessment had similar findings as a Canadian study that also saw effective performance of a system years after its construction (Sprakman et al. 2020).

Our estimates of runoff infiltration and pollutant mass loadings presented herein are likely conservative. Capturing 100% of flows entering the BCRG from all storms was not possible. On some occasions, during the most intensive period of the larger storms, portions of the runoff flow at Inlet 3 overtopped the curb enclosing the inlet pad, directly entering the garden. This observation indicated that even more runoff entered the BCRG than was measured. Therefore, for the larger storms, the findings presented for both inflow and mass loadings most likely underestimate these variables and present conservative assessments.

The length of time between storm events affects pollutant loading, which brings importance to the BCRG’s ability to infiltrate the seasonal first flush (Stenstrom and Kayhanian 2005). The seasonal first flush phenomenon occurs when the season’s initial stormwater flow mobilizes the highest pollutant concentrations relative to subsequent storm events. Thus, potential changes to wet weather events due to climate variability in combination with urban impervious surfaces increase the potential loading of stormwater pollutants within these systems. This highly polluted runoff can impact ecological functions in freshwater and marine habitats, as well as human health of people exposed to these pollutants. The storm event on 20–21 November 2016 appears to most closely meet the definition of a seasonal first flush event. It was a moderate size (16 mm), but it was preceded by a long antecedent period of several dry summer months, except for a few fully infiltrated small storms during the previous two months. Thus, the long antecedent period without outflow to Ballona Creek should have contributed to the accumulation of pollutants flowing to the BCRG.

The management of first flush pollution often involves the use of the 85th percentile, 24 hr storm in the design of detention basins and other Best Management Practices. This criterion is approximately 28 mm in the study area. A total of five storms (5 January, 5 March, and 15 December 2016, 22 January and 7 February 2017) exceeded this threshold

but may not fit the definition of seasonal first flush as all had short antecedent dry periods ranging from a few days to three weeks. Table 2 shows these five storms as well the 20 November 2016 storm. Both pollutant concentrations and loadings tended to be higher for the first flush storms that were sampled. For example, the 20 November 2016 storm showed considerably higher concentrations of *E. coli*, Enterococci, metals, and organics with higher amounts in the outlet than in the inlet samples in some cases. This result suggests that contaminants accumulated in the garden from a seasonal first flush. The higher flows from these five storms likely dislodged pollutants that accumulated during dry periods. However, there were also exceptions to this pattern. For example, the storm on 5 March 2016 saw some of the lowest concentrations for PAHs, metals, and TSS. The BCRG performed reasonably well under the circumstances by reducing both pollutant concentrations and loads in most cases.

Increasing levels of total rainfall were directly related to the volume of runoff infiltrated into the garden and inversely related to the percent retention. Smaller storms had 100% infiltration, and the percentage decreased for the larger storm events. The best fit multiple linear regression models identified both total rainfall and storm duration as important drivers of the amount of runoff infiltrated into the garden, while total rainfall and storm intensity were the important drivers of percent overall infiltration. Both models explained a substantial amount of the variance.

The overall pollutant retention capacity within the BCRG, in terms of mass loadings, averaged 72% (range of 48-84%, depending on the pollutant). This result compared favorably with other bioretention studies, offering further proof of the benefit and efficiency of bioretention systems within Mediterranean climates. In contrast to the north and eastern parts of the country that receive more constant rainfall, the wet season in the Los Angeles region is generally October through April, followed by a longer dry season from May through September. A previous field-scale study of two bioretention systems in Australia found averages of 80-90% retention for suspended solids and heavy metals (Hatt et al. 2009) while a study from New Jersey measured average retention of fecal coliforms at 91.6% (Rusciano and Obropta 2007). The BCRG achieved comparable retention levels for solids and metals but showed lower retention levels for bacteria. It is difficult to determine whether occasional increases were runoff-related or related to natural conditions or other processes within the BCRG. This uncertainty merits further studies relating to bacteria sourcing and their patterns, including relating to sunlight exposure times, as it is possible the BCRG became a temporary refuge in the absence of direct sunlight. Regardless, bacterial densities entering the garden were reduced, on average, by 53% for *E. coli* and 48% for enterococci.

Overall pollutant loading estimates were based on calculating mean concentrations from pooled inlets and outlets during each storm. Single samples of runoff were collected at each inlet and outlet over the course of a storm for various pollutant analyses (except for FIB where three replicates were collected), due to resource availability. This limitation may have resulted in errors in estimating loading for individual storm events (Leecaster et al. 2002), but by pooling concentration data the resulting loading estimates are likely to be reasonable.

Results of this study could be useful to municipalities requiring peak flow attenuation, increased infiltration, pollution retention, and/or capture/storage of storm runoff as part of local codes or stormwater management strategies for new construction and redevelopment projects. Many of the approaches used in the BCRG can be applied to other

projects where urban development is a hydrologic concern or pollutant reduction is a goal.

Although the performance of the garden proved to be functional, it is possible for management issues like maintenance and pollutant ownership to hinder the efficiency of similar systems. Bioretention systems have occasionally been built as quick fixes and not maintained with longevity in mind. It is often unclear where the maintenance responsibility lies. The design goals (i.e., metal retention or peak flow attenuation) must be carefully planned and are met when regularly inspected and maintained (Hunt et al. 2012). This particular system underwent regular maintenance through the use of volunteers to remove invasive plants and care for native ones. Trash was periodically removed by site managers before and after wet seasons, but it was not quantified as part of this study. In addition to maintenance and upkeep, these systems bring up the important issue of pollutant ownership. In restoring more natural drainage to urban areas, pollutants are captured rather than rushing out to water bodies. This capture, although beneficial to nearby and downstream communities, has the potential to create ‘ownership’ of pollutants (Davis 2005). Ownership creates additional questions that need to be answered about the responsibility for testing, maintaining, and even replacing soil or other bioretention media when they reach toxic or unhealthy levels as determined by regulatory agencies or the community. The fate and effect of retaining pollutants on site was outside the scope of this study. However, it is possible that some pollutants are retained long-term within the garden, while others may be metabolized or transported to soils, groundwater, or biomass. The multiple benefits that the system provides such as cleaner downstream waters and native habitat must be weighed against long-term fate considerations, and management actions such as soil replacement or amendments may need to be considered.

Despite the increase in information gained from this study about bioretention in Mediterranean climates and specifically in the Los Angeles region, additional research is still needed. Specific topics like pollutant fate, system lifespan, increases in biodiversity, and additional ecosystem services provided would be of great benefit in promoting these LID options. Much of the current research suggests that bacteria experience die-off within a few days of bioretention capture (Zhang et al. 2010), but this situation depends heavily on microbial conditions within the system as well as the composition of the runoff. Nutrient and contaminant uptake levels can vary with surrounding land uses as well as climatic conditions. The organic pollutants like polyaromatic hydrocarbons are usually captured near the surface in mulch or soil media due to the hydrophobicity of the compounds (Hunt et al. 2012). The metals were also found to primarily gather in the higher levels of soil media (Li and Davis 2008). This could mean periodically replacing this upper layer would elongate the lifespan of the system. Additional work is needed to determine the role of plants in metal sequestration as well as soil media. Consideration should also be given to native plant palettes for rain gardens; plant selection should correspond to current and future site conditions, desired benefits, and overall function (Farrell et al. 2022).

Another important area of study is to better characterize additional ecosystem services provided by these LID systems. They offer green spaces and ecosystem services that have the potential to benefit human health as well as promote biodiversity. They can help combat heat islands that are frequently associated with urban areas, mitigate flooding, and recharge aquifers. The longevity of bioretention systems needs to be studied further to ascertain their potential impact on stormwater management as a whole.

Conclusions

This two year study sheds further light on bioretention systems usage within Mediterranean climates such as southern California, although more research is recommended to truly measure longevity, pollutant fate, and ecosystem services provided by bioretention systems. The grand mean was 72% pollutant retention across all sampled analytes combined with an average 74% stormwater infiltration, which shows that these nature-based bioretention systems can truly benefit stormwater management in urban areas while providing a myriad of additional benefits.

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Appendices

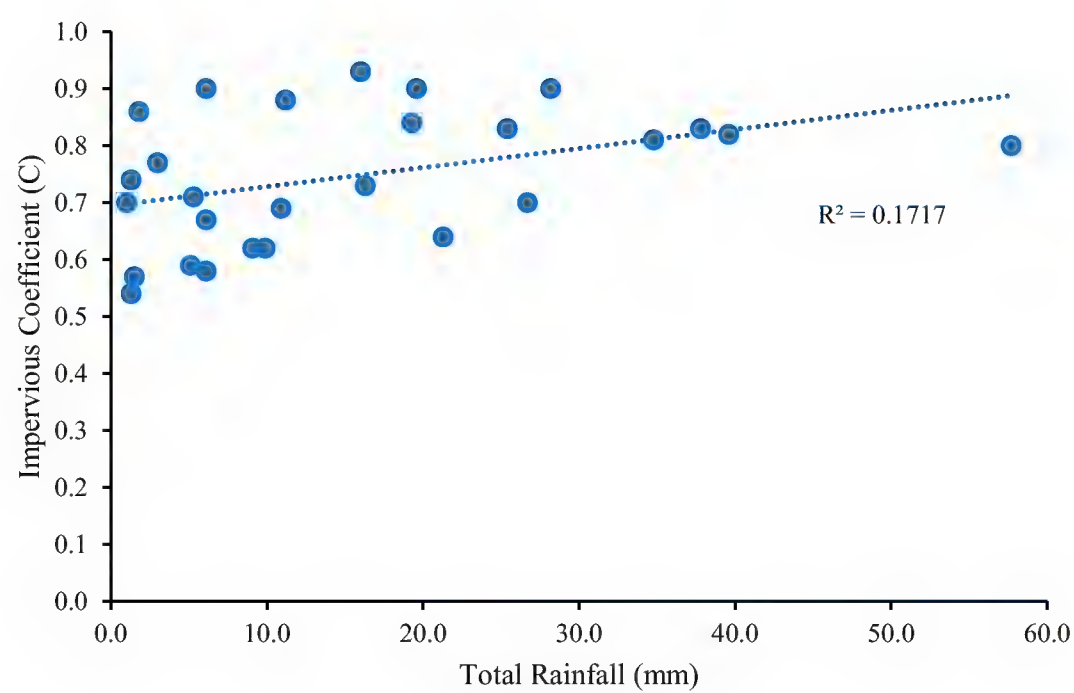
Appendix 1: Runoff Coefficients and Total Rainfall

The table below shows the runoff coefficients ($\hat{C}$) for each storm. The $\hat{C} = 1.00$ result is an outlier because it results in zero rainfall loss. We suspect that it may have resulted from higher than usual flow monitoring errors and to some extent from runoff contributions from a larger storm (6.1 mm of rainfall) on the previous day, which may have caused an overlap of runoff flow at the inlet weirs and difficulty in splitting runoff between the two closely spaced storms. This result is probable because the volume-weighted average value of the two storms is more reasonable at a value of 0.73. As such, it is likely that some overlap of runoff artificially decreased the runoff coefficient of the first storm while increasing it for the second storm. A similar situation may have occurred during the storms of 9 and 10–11 January 2017, where higher outlier $\hat{C}$ values were compensated with lower values from the preceding storm.

Storm date	Rainfall total (mm)	Direct runoff volume from rainfall (L)	Impervious coefficient ($\hat{C}$) in upstream watershed	Volume infiltrated in upstream watershed (L)	Percent infiltration in upstream watershed (%)
5 Jan 16*	34.8	1,293,612	0.81	297,682	18.7
31 Jan 16*	6.1	160,624	0.58	118,143	42.4
5–7 Mar 16*	28.2	1,163,547	0.90	125,750	9.8
11 Mar 16*	11.2	450,448	0.88	60,625	11.9
20–21 Nov 16*	16.0	681,800	0.93	49,963	6.8
26 Nov 16	5.1	137,712	0.59	94,593	40.7
15–16 Dec 16*	37.8	1,439,449	0.83	291,229	16.8
21–22 Dec 16	16.3	540,704	0.73	202,675	27.3
30 Dec 16	6.1	185,433	0.67	93,334	33.5
31 Dec 16	1.5	69,566	1.00	126	0.2
4–5 Jan 17*	10.9	346,488	0.69	152,969	30.6
7 Jan 17	1.8	69,966	0.86	11,341	13.9
9 Jan 17	21.3	623,491	0.64	352,193	36.1
10–11 Jan 17	6.1	250,123	0.90	28,644	10.3
11–12 Jan 17	26.7	852,338	0.70	367,267	30.1
19 Jan 17*	19.3	742,148	0.84	140,614	15.9
20 Jan 17	25.4	969,264	0.83	192,265	16.6
22–23 Jan 17	57.7	2,108,555	0.80	528,115	20.0
3 Feb 17	5.3	172,939	0.71	70,982	29.1
6 Feb 17	19.6	808,083	0.90	86,294	9.6
7 Feb 17	9.1	259,303	0.62	158,847	38.0
7–8 Feb 17	1.5	39,513	0.57	30,179	43.3
10–11 Feb 17	9.9	283,080	0.62	169,916	37.5
17–18 Feb 17*	39.6	1,492,966	0.82	319,019	17.6
19–20 Feb 17	1.3	43,189	0.74	14,887	25.6
21 Feb 17	1.0	32,634	0.70	13,827	29.8
26 Feb 17	1.3	31,502	0.54	26,574	45.8
21–22 Mar 17	3.0	107,285	0.77	32,099	23.0
Total	423.9	15,355,763	—	4,030,000	—
Average	15.1	548,420	0.76	144,000	24.3
Maximum	57.7	2,108,555	1.00	528,000	45.8
Minimum	1.0	31,502	0.54	126	0.2
Standard Error	1.6	103,108	0.02	25,135	2.4

* Water quality was monitored during the storm event.

The figure below depicts the calculated $\hat{C}$ coefficients as a function of total rainfall. The $\hat{C} = 1$ outlier is not included. The graph shows that the $\hat{C}$ coefficients were insensitive to changes in the total rainfall measured during the study, as evidenced by the low R^2 value and wide distribution of points for any given total rainfall range. This finding was consistent with the common approach of assuming runoff coefficients as constant values. Considerable variability is also evident, especially at the lower rainfall values, which may reflect the exacerbated effect from initial rainfall abstraction losses, antecedent conditions, or other factors, which may have caused more variable $\hat{C}$ values at lower rainfalls. Notwithstanding the weak correlation in the figure below and the previously discussed $\hat{C} = 1.00$ outlier, the runoff values appear to decrease slightly at lower total rainfall. It is hypothesized that $\hat{C}$ values would approach zero in even smaller storms, as all the rainfall tends to be fully absorbed by initial losses and results in zero runoff.



Appendix 2: Statistical Results for Multiple Linear Regressions

Table A1. Akaike information criterion (AIC) results to evaluate the best fit multiple linear regression model. Asterisks indicate the best fit models for each dependent variable based on AIC results.

Model #	Dependent variable	Explanatory variables	AIC
LM1	Volume Infiltrated (L)	Duration (hr), Total Rainfall (mm), Intensity (mm/hr)	738.481
LM2		Total Rainfall (mm), Intensity (mm/hr)	748.943
LM3*		Duration (hr), Total Rainfall (mm)	737.700
LM4		Duration (hr), Intensity (mm/hr)	738.888
LM1	Percent Infiltration (%)	Duration (hr), Total Rainfall (mm), Intensity (mm/hr)	221.171
LM2*		Total Rainfall (mm), Intensity (mm/hr)	219.396
LM3		Duration (hr), Total Rainfall (mm)	229.870
LM4		Duration (hr), Intensity (mm/hr)	227.644

Model (LM3) statistical results for volume infiltrated multiple linear regression.

Coefficients	Estimate	Std. Error	t value	Pr(> t)	Significance
Intercept	29691	40004	0.742	0.4649	NA
duration_hr	7733	1936	3.995	0.0005	<0.001
total_rainfall_mm	7837	1720	4.555	0.0001	<0.001

Residual standard error: 116800 on 25 DF.
Multiple R² = 0.7177, Adjusted R² = 0.6951.
F_{2,25} = 31.78, p = 1.362e-07.

Model (LM2) statistical regression results for percent infiltration multiple linear regression.

Coefficients	Estimate Std.	Error	t value	Pr(> t)	Significance
Intercept	105.3762	3.3263	31.680	0.0000	<0.001
total_rainfall_mm	-1.0484	0.2162	-4.849	0.0001	<0.001
intensity_mm_hr	-16.7241	4.0179	-4.162	0.0003	<0.001

Residual standard error: 11.16 on 25 DF.
Multiple $R^2 = 0.8552$, Adjusted $R^2 = 0.8437$.
 $F_{2,25} = 73.85$, $p = 3.221\text{e-}11$.

What Habitat Complexity Might Inform Us About Platform Decommissioning: Comparing Fish Assemblages at a California Offshore Platform with Two Nearby Seep Tents

Milton S. Love,* Li Kui, Merit McCrea, Ann S. Bull, and Mary M. Nishimoto

Marine Science Institute, University of California, Santa Barbara, California 93106

Abstract.—In August 2023, we conducted a fish survey around Platform Holly and at two nearby seep tents, in southern California, using a remotely operated vehicle. We divided the structures into four habitats: Platform Holly midwaters, Platform Holly base, seep tents towers, and seep tents bases. The platform and the seep tents are similar in the following ways: 1) all are fabricated of steel, 2) all are in approximately the same bottom depth, 3) all are physically close together (and thus in the same water mass and likely exposed to the same current patterns), and 4) all were surveyed within a three-day period using the same methodology. They differ in that, compared to the other three habitats, the seep tent bases are more complex, having numerous ledges and holes. Over all four habitats, we observed a minimum of 36 fish species, representing 6,541 individuals and, at all habitats, the vast majority of fishes were rockfishes (*Sebastes* spp.). In addition, most of the fishes were small, and the majority at all sites, were juveniles. However, unlike at the other habitats where only juveniles were found, at the more complex seep tents bases we observed large, mature fishes of several species (e.g., copper and vermilion rockfishes). Based on these observations, we hypothesize that adding complexity to the bottom of Platform Holly, as part of the decommissioning process, will increase the density of large, mature fishes, particularly of those species that are usually associated with sheltering sites.

With perhaps 7,000 offshore oil and gas platforms worldwide (Techera and Chandler 2015), and with many of these structures drawing from increasingly depleted fields, more attention is being paid to the ultimate disposition of these structures (the various horizontal, diagonal, and vertical members are the *jacket*). This decision-making process, termed *decommissioning*, can be complex, as it often involves biology, engineering, sociology, and politics (Techera and Chandler 2015; Scarborough Bull and Love 2019; InterAct 2020). There are various potential decommissioning options, ranging from leaving the entire structure in place, to removing the upper parts of the jacket (*topping*), to complete removal (Schroeder and Love 2004; Scarborough and Love 2019). Thus far, respecting California platforms, most decommissioning options have centered around either topping (in this instance removing the jacket to a depth of about 26 m (85 ft), or complete removal.

Regarding the role that platforms may play as habitat for fishes, at least in a few geographical regions there is a fairly robust literature (e.g., Love et al. 2019a; McLean et al. 2019; Harvey et al. 2021), and a few papers discuss the potential effects of these assemblages on regional populations (Love et al. 2005, 2006; Birt et al. 2024). However, and with only a very few exceptions [notably Claisse et al. (2015)], there has been no published discussions regarding adding additional complexity to these structures (assuming some parts of the jacket

* Corresponding author: love@lifesci.ucsb.edu



Fig. 1. Location of Platform Holly and the two seep tents, Santa Barbara Channel, southern California.

remain in place). This would take place before or during the decommissioning process, to achieve such goals as increasing fish or invertebrate production, or otherwise altering the makeup of the remaining assemblages. To that end, we have recently conducted a survey of the fishes living in association with three human-made structures off southern California that are in close proximity to one another, yet have somewhat different structural architecture. This afforded us the opportunity to examine how habitat complexity might influence both the assemblages and size structures of fishes, and how this knowledge might be useful during the decommissioning of platforms in that region.

We conducted these surveys around two types of structures: 1) Platform Holly and 2) two nearby seep tents. Platform Holly ($34^{\circ} 22' N$, $119^{\circ} 52' W$) is a steel fixed-type platform installed by Atlantic Richfield in 1966, with first production in 1968; production ceased in 2015. Production included both oil and gas (the platform is now permanently shut-in). The platform stands in ~ 60 m of water, about 2.9 km from shore, in California state waters (Fig. 1). Platform Holly's dimensions are 18×30 m at the surface, and 36×48 m at the sea floor, with a footprint of $1,728 \text{ m}^2$ (Love 2019). Similar to almost all offshore platforms, Holly's *midwater* jacket (here defined as between the surface and about 2 m above the bottom) is structurally relatively simple, as it is composed of cylindrical horizontal and diagonal crossbeams, and vertical cylindrical pilings (Figs. 2, 3) (Love et al. (2019b) for a discussion of the one California platform with a complex midwater jacket). Holly midwaters have four horizontal crossbeams at depths of 7.6 m, 19.8 m, 35.0 m, and 49.3 m. Surrounding the platform is a shell mound created from the shells of mussels (*Mytilus* spp.) that encrust the upper parts of the jacket of all California platforms (Bomkamp et al. 2004), and fall to the sea floor. All California offshore platforms were designed to have a crossbeam resting at or near the bottom. At a majority of platforms, some or all of this crossbeam is undercut, forming a long crevice, thus creating substantial benthic habitat complexity. However, the crossbeam at the base of Holly's jacket is mostly buried by mussel shells (eTrac 2014), thus creating a somewhat less complex habitat (Fig. 3).

The two seep tents rest 1.6 km to the east of Platform Holly (Fig. 1). These are steel pyramid-shaped structures, each with a tower arising out of the center (Fig. 4). The seep tents are described in Rintoul (1982): "In 1982, a seep containment device was placed on the sea floor 1.5 km east of oil platform Holly in a joint effort by ARCO and Mobil oil companies. This device comprises two steel pyramids or tents measuring 100 by 100 feet [30.5 m] each that capture emissions from

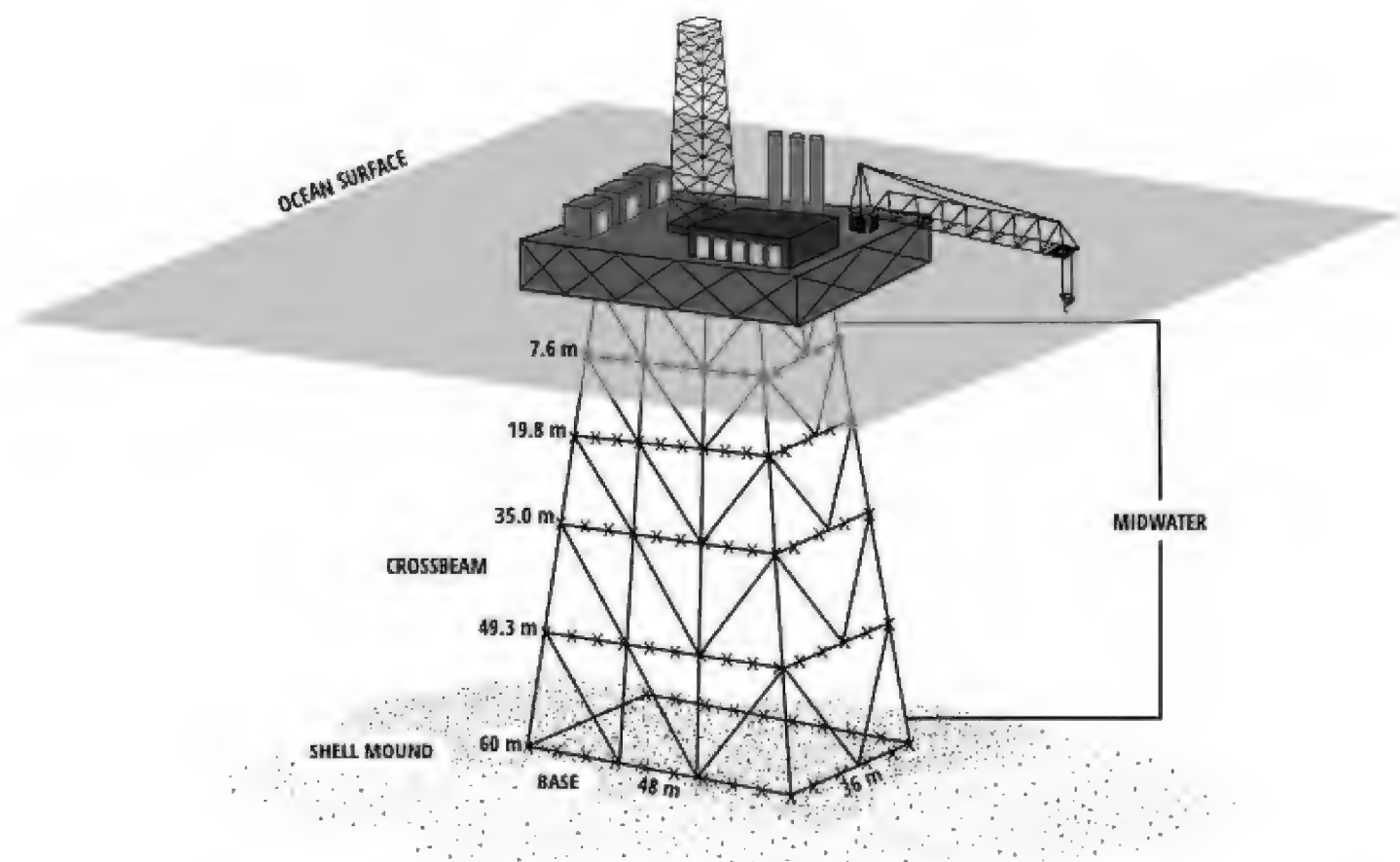


Fig. 2. Schematic of Platform Holly. The transect paths are marked with “x”s. Note that the transects extended all around the platform jacket (x’s not shown on two of the sides).

numerous hydrocarbon seeps on the sea floor. Captured gas is sent ashore through a sea floor pipeline for commercial sale and oil is periodically removed at the tents.” Each tower, hollow and designed to capture the oil that had migrated from the sea floor along with the gas, is 9.1 m tall and 1.5 m in diameter. From the base of a seep tent to the apex of the tower is 15 m [the apex is at a depth of 51 m). During our survey, we determined that the bases of these tents rest at a depth of about 66 m. Importantly, the seep tent bases, compared to their towers or to the jacket of Platform Holly, are physically quite complex with numerous ledges and holes (Fig. 3).

The similarities of these three structures are the following: 1) all are fabricated of steel, 2) all are in about the same bottom depth, 3) all are physically close together (and thus in the same water mass and likely exposed to the same current patterns), 4) all were surveyed within a 3 d period using the same methodology, and 5) our experience is that none of these habitats are fished by either recreational or commercial fishermen. However, these habitats do differ in their structural complexity, allowing us to explore this as a possible influence on both the various species assemblages, and on the species’ size frequencies. Based on these similarities, we hypothesized the three structures would harbor similar species assemblages, with similar size frequencies.

Methods and Materials

We conducted surveys around four habitats: 1) Platform Holly’s jacket, and 2) Platform Holly’s base, 3) the two seep tent towers, and 4) the two seep tent bases. These surveys were conducted with a Remotely Operated Vehicle (ROV). Surveys were conducted with a Falcon DR-class ROV, operated by Aqueous Corporation, and deployed from the support vessel *Danny C*. The entire survey of the three structures were conducted over a three-day period, during 10-12 August 2023. Fugro West Incorporated tracked the course of the ROV. While the ROV was equipped with its own video camera, we added a high definition SubC 1CamMk6

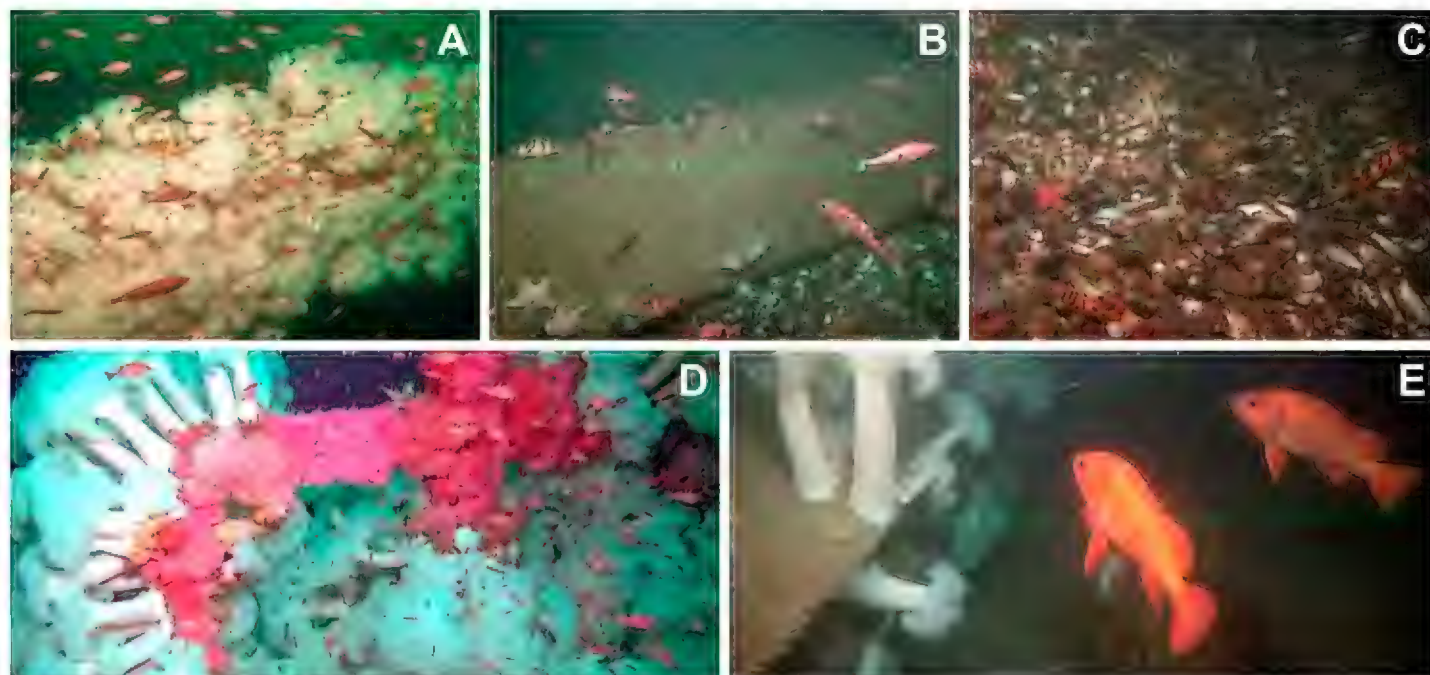


Fig. 3. Images of the four habitats surveyed in this study. A = A Platform Holly midwater crossbeam encrusted with *Metridium senile* (Linnaeus, 1761). Fishes are young-of-the-year bocaccio and squarespot rockfish. B = The crossbeam at the base of Platform Holly. This is one of the few places where the crossbeam is exposed. Fishes include calico rockfish, halfbanded rockfish, and olive rockfish. C = A more typical scene at the base of Platform Holly, where the bottom crossbeam has been covered over with mussels that have fallen from the upper parts of the platform. D = A closeup of a seep tent tower. The structure is covered in white *Metridium farcimen* (Brandt, 1835) and red *Corynactis californica* Carlgren, 1936. YOY rockfish are dense here. E = Two mature vermilion rockfish hover near the base of a seep tent. Note the seep tent ledges which add complexity to the structure.

and used the footage from that to analyze the fishes. A pair of green lasers were positioned 6 cm apart on each side of the HD video camera and were visible in at all times. In the laboratory, we identified and recorded all fishes to the lowest possible taxon (using the software SeaGIS EventMeasure (www.seagis.com.au), and estimated their lengths by comparing the size of a fish to the known spacing of the laser spots. Thus, the laser points did not have to pass along a fish for a length estimate to be made. This laser system has been used in many other Pacific Coast submersible fish studies (e.g., Yoklavich et al. 2007; Love et al. 2019a; Laidig and Yoklavich 2016). We have used common names for the fishes and both common and scientific names of all species are listed in Table 1. As the area surveyed differed considerably among the various habitats, we present not only the minimum number of species observed at each, but also the species density, defined as total number of minimum species divided by the area swept.

We conducted Welch's ANOVA to examine fish size differences across the four habitats. This test, an adaptation of the standard ANOVA, is more robust when variances are unequal. Subsequently, a Games-Howell Post-hoc test identified significant differences in fish length between habitats (Nicholson and Clements 2023). The post-hoc test utilized Welch's degrees of freedom correction and Tukey's studentized range distribution for p-value computation, and it compared all possible habitat pairs for mean fish length, adjusting for multiple comparisons. R package "rstatix" was used for the Welch's ANOVA and Games-Howell Post-hoc tests (Kassambara 2023). All statistical analysis was conducted in R (R Core team 2023).

Results

Over all four habitats, we observed a minimum of 36 fish species (Table 1), representing 6,541 individuals (Tables 2-5).

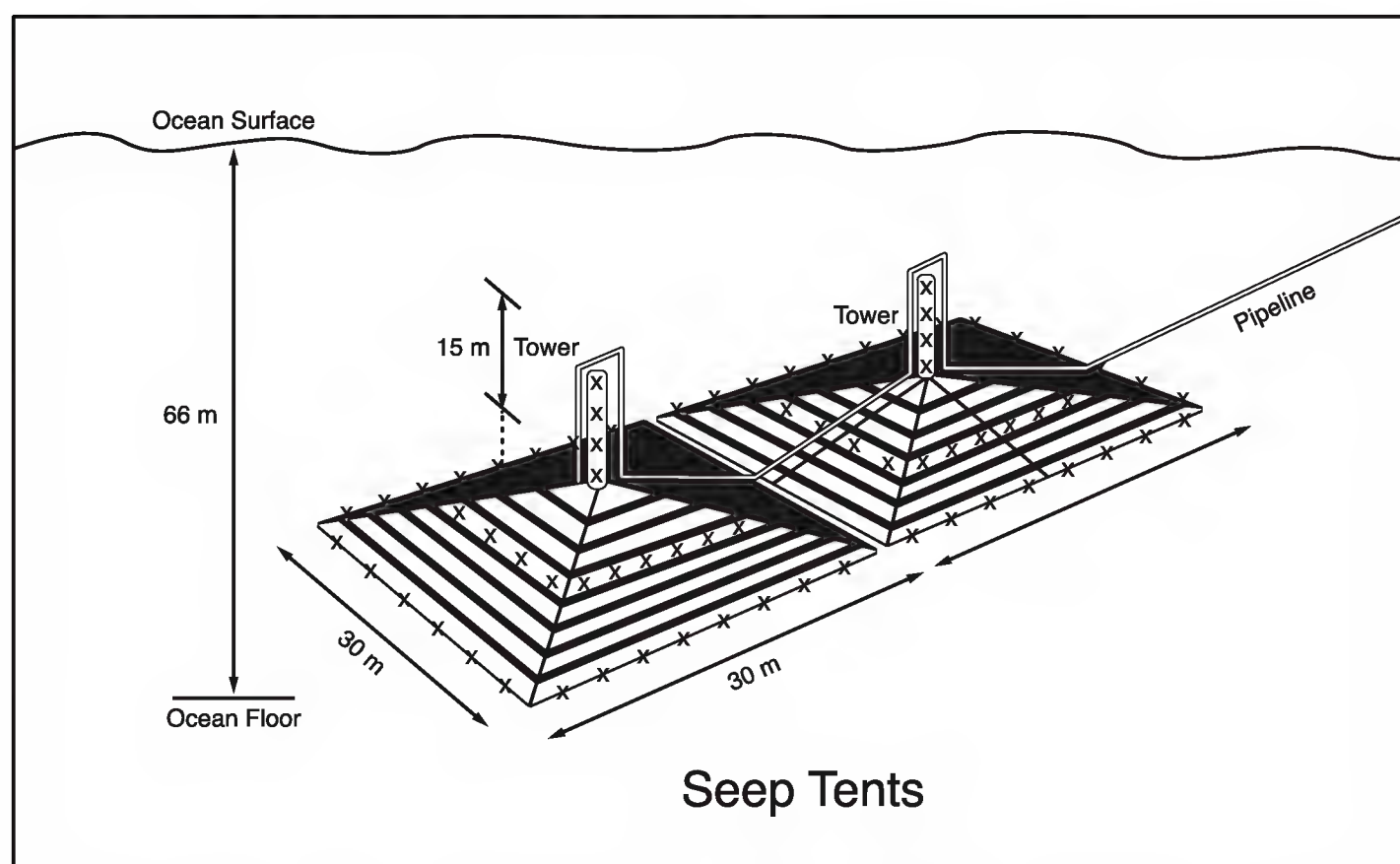


Fig. 4. Schematic of the two seep tents. The transect paths are marked with “x”s.

Platform Holly midwaters.—In the midwaters of Platform Holly (at depths of 7.6 m, 19.8 m, 35.0 m, and 49.3 m), we observed 4,385 fishes, and a minimum of 23 species, of which at least 12 taxa were rockfishes (genus *Sebastes*) (Table 2). Rockfishes represented 93.7% of all fishes observed. Unidentified YOY rockfishes dominated the assemblage, with bocaccio, blue rockfish, painted greenling, and squarespot rockfish among the most prevalent identifiable species. Most of the fishes we observed were small ($\bar{x} = 8.0 \pm 4.6$ cm s.d.) (Fig. 5).

Platform Holly base.—We observed 1,199 fishes, and a minimum of 20 fish species (at least 14 of which were rockfishes) associated with the base of Platform Holly (at a depth of 60 m) (Table 3). Calico rockfish, shortbelly rockfish, unidentified YOY rockfish, halfbanded rockfish, painted greenling, and vermilion rockfish were the dominant species or species groups. Overall, rockfishes comprised 94.7% of all fishes observed. Lengths were slightly larger than in the midwaters ($\bar{x} = 11.0 \pm 5$ cm s.d.) (Fig. 6).

Seep tents towers.—The seep tent towers (ranging in depth from 42–51 m) harbored the fewest individual fishes (176), and the fish assemblage associated with those towers had the fewest minimum number of species (9). Almost all of the fish were unidentified YOY rockfish and, overall, 98.9% of all fishes were rockfishes (Table 4). Mean length of fishes in this habitat was 11.6 ± 11.0 cm (Fig. 5).

Seep tents bases.—We observed 781 fishes, of a minimum of 24 species (Table 5), the highest number of species in this study, associated with the two seep tent bases (surveys conducted at 66 m and 59 m). YOY rockfishes were by far the most important, followed by vermilion rockfish, pink seaperch, calico rockfish, halfbanded rockfish, and copper rockfish. Rockfishes comprised 83.6% of all fishes observed. Mean length of fishes in this habitat was 17.1 ± 16.6 cm (Fig. 6).

Most of the fishes we observed in this study were relatively small (Figs. 5, 6) and Welch's ANOVA indicated a highly significant difference in the size variable across different habitat types ($F = 350.813$, $p < 0.001$). To pinpoint where these differences lay, a Games-Howell Post-hoc test

Table 1. Fish species documented at Platform Holly and at the seep tents, based on ROV surveys conducted in August 2023. Species alphabetized by common name.

Common name	Scientific name
Blackeye goby	<i>Rhinogobiops nicholsii</i> (Bean, 1882)
Blacksmith	<i>Chromis punctipinnis</i> (Cooper, 1863).
Blue rockfish	<i>Sebastes mystinus</i> (Jordan & Gilbert, 1881)
Bocaccio	<i>Sebastes paucispinis</i> Ayres, 1854
Brown rockfish	<i>Sebastes auriculatus</i> Girard, 1854
Cabazon	<i>Scorpaenichthys marmoratus</i> (Ayres, 1854)
Calico rockfish	<i>Sebastes dallii</i> (Eigenmann & Beeson, 1894)
Copper rockfish	<i>Sebastes caurinus</i> Richardson, 1844
Cowcod	<i>Sebastes levis</i> (Eigenmann & Eigenmann, 1889)
Flag rockfish	<i>Sebastes rubrivinctus</i> (Jordan & Gilbert, 1880)
Garibaldi	<i>Hypsypops rubicundus</i> (Girard, 1854)
Gopher rockfish	<i>Sebastes carnatus</i> (Jordan & Gilbert, 1880)
Halfbanded rockfish	<i>Sebastes semicinctus</i> (Gilbert, 1897)
Kelp bass	<i>Paralabrax clathratus</i> (Girard, 1854)
Kelp greenling	<i>Hexagrammos decagrammus</i> (Pallas, 1810)
Kelp rockfish	<i>Sebastes atrovirens</i> (Jordan & Gilbert, 1880)
Lavender sculpin	<i>Leiocottus hirundo</i> Girard, 1856
Lingcod	<i>Ophiodon elongatus</i> (Girard, 1854)
Longspine combfish	<i>Zaniolepis latipinnis</i> Girard, 1858
Northern ronquil	<i>Ronquilus jordani</i> (Gilbert, 1889)
Olive rockfish	<i>Sebastes serranoides</i> (Eigenmann & Eigenmann, 1890)
Painted greenling	<i>Oxylebius pictus</i> (Gill, 1862)
Pile perch	<i>Phanerodon vacca</i> (Girard, 1853)
Pink seaperch	<i>Zalemnius rosaceus</i> (Jordan & Gilbert, 1880)
Rosy rockfish	<i>Sebastes rosaceus</i> Girard, 1854
Sharpnose seaperch	<i>Phanerodon atripes</i> Girard, 1853
Shortbelly rockfish	<i>Sebastes jordani</i> (Gilbert, 1896)
Shortspine combfish	<i>Zaniolepis frenata</i> Eigenmann & Eigenmann, 1889
Squarespot rockfish	<i>Sebastes hopkinsi</i> (Cramer, 1895)
Stripefin ronquil	<i>Rathbunella alleni</i> Gilbert, 1904
Stripetail rockfish	<i>Sebastes saxicola</i> (Gilbert, 1890)
Topsmelt	<i>Atherinops affinis</i> (Ayres, 1860)
Treefish	<i>Sebastes serriceps</i> (Jordan & Gilbert, 1880)
Unidentified fishes	
Unidentified ronquil	Family Bathymasteridae
Unidentified sanddab ¹	<i>Citharichthys</i> spp.
Vermilion or sunset rockfish ²	
White seaperch	<i>Phanerodon furcatus</i> Girard, 1854
Widow rockfish	<i>Sebastes entomelas</i> (Jordan & Gilbert, 1880)
Yellowtail rockfish	<i>Sebastes flavidus</i> (Ayres, 1862)
<i>Sebastomus</i> sp. ³	
YOY rockfish ⁴	Unidentified <i>Sebastes</i> sp. young-of-the-year

¹ *Citharichthys sordidus* (Girard, 1854) (Pacific sanddab) and/or *Citharichthys stigmaeus* Jordan & Gilbert, 1882 (speckled sanddab).
² Either *Sebastes miniatus* (Jordan & Gilbert, 1880) and/or *Sebastes crocotulus*.
³ Likely *Sebastes rosaceus*.
⁴ Likely primarily widow rockfish and squarespot rockfish.

was performed (Table 6). The results showed significant differences in fish sizes between most pairs of habitats, except between the platform base and the seep tents towers, where the difference was not statistically significant ($p = 0.937$). Importantly, the fishes at the seep tents bases had the overall greatest mean length compared to the other three habitats ($p < 0.01$). This difference was primarily

Table 2. Fish species observed along the four midwater crossbeams (7.6 m, 19.8 m, 35.0 m, and 49.3 m) of Platform Holly, based on ROV surveys conducted in August 2023. YOY refers to young-of-the-year unidentifiable below the genus level. Fishes are listed by densities (individuals 100 m⁻²). Scientific names are given in Table 1.

Species	Number	Density
YOY rockfish	3,357	361.7
Bocaccio	229	25.0
Blue rockfish	215	23.5
Painted greenling	161	17.6
Squarespot rockfish	97	10.6
Topsmelt	74	8.1
Widow rockfish	73	8.0
Copper rockfish	50	5.5
Kelp rockfish	34	3.7
Cabazon	26	2.8
Olive rockfish	21	2.3
Calico rockfish	16	1.8
Halfbanded rockfish	8	0.9
Blacksmith	6	0.7
Gopher rockfish	6	0.7
Kelp bass	2	0.2
Treefish	2	0.2
White seaperch	2	0.2
Garibaldi	1	0.1
Kelp greenling	1	0.1
Lavender sculpin	1	0.1
Pile perch	1	0.1
Sharpnose seaperch	1	0.1
Yellowtail rockfish	1	0.1
Minimum Number of Species	23	
Total Number	4,385	
Percent Rockfishes	93.7%	
Total Density		478.6

due to the presence of mature vermilion and copper rockfishes at the seep tents bases, and mostly immature vermilion and copper rockfishes at the platform base (Fig. 7).

With a few exceptions, Platform Holly acted as a nursery ground for a variety of species (Figs. 8a, b, c, d). In the platform midwaters, almost all of the most abundant species were juveniles, and most were YOY rockfish (Fig. 8a). The platform base assemblage was composed primarily of juveniles of a range of benthic-oriented species (i.e., YOY rockfish, shortbelly rockfish, and halfbanded rockfish), and adults of a few dwarf taxa (e.g., calico rockfish and painted greenling) (Fig. 8b). Virtually all of the fishes observed at the seep tents towers were YOY rockfish (Fig. 8c). Unlike the other three habitats, the fish assemblage at the seep tents bases harbored substantial numbers of both juvenile fishes (e.g., YOY rockfish, halfbanded rockfish, and calico rockfish) and mature fishes (e.g., copper rockfish, vermilion rockfish, squarespot rockfish, blue rockfish, and pink seaperch) (Figs. 7, 8d).

Discussion

The vast majority of fishes in the platform and seep tents midwaters were juveniles, most of them were YOY rockfish that were newly recruited from the plankton, demonstrating that

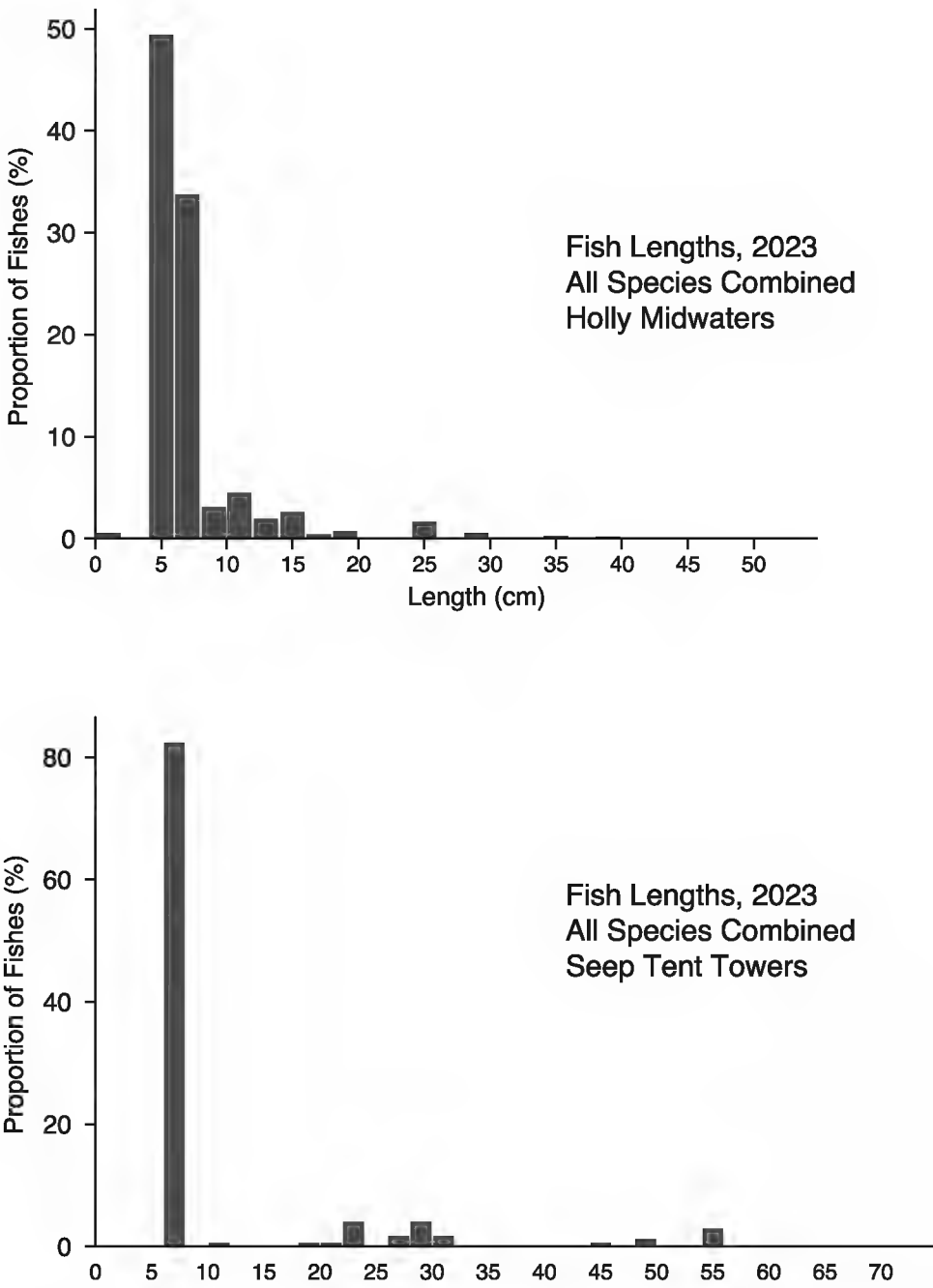


Fig. 5. Size structure of all fishes observed in the midwaters of Platform Holly and at the seep tent towers, based on ROV surveys conducted in August 2023. Midwaters, N = 4,385, towers, N = 1,763.

these habitats have a role as nursery grounds for a range of taxa. Among the species that were identifiable, juvenile bocaccio, blue rockfish, painted greenling, and squarespot rockfish were dominant, and these species are typical of both other California platform midwaters, as well as high-relief natural reefs (Love et al. 2009, 2019a). At the platform base, the dominant species or species groups were YOY rockfish, juveniles and/or adults of five dwarf species (calico rockfish, shortbelly rockfish, halfbanded rockfish, painted greenling, and blackeye goby), along with juvenile copper rockfish and vermilion rockfish. Most of these species, with the exception of painted greenling, are usually found over hard, but low sea floors, such as cobble or small boulders. It is likely that the shells covering the bottom around Platform Holly serve this same function. The seep tents towers were almost exclusively the domain of YOY rockfish. At the seep tent bases, along with YOY rockfish, there were also adults of such species as pink seaperch and squarespot rockfish. However, and uniquely among these four habitats, at the seep tents bases there were also relatively high densities of mature vermilion and copper rockfishes, as well as lower densities of mature brown rockfish, bocaccio, and lingcod. Based on the size frequencies of these fishes, it seems likely that the seep tents bases are parturition (i.e., rockfishes) and spawning (i.e., lingcod) grounds for these fishes. Thus, it can be argued that Platform

Table 3. Fish species observed at the base of Platform Holly, based on ROV surveys conducted in August 2023. YOY refers to young-of-the-year unidentifiable below the genus level. Fishes are listed by densities (individuals 100 m⁻²). Scientific names are given in Table 1.

Species	Number	Density
Calico rockfish	448	170.0
Shortbelly rockfish	292	110.6
YOY rockfish	231	83.0
Halfbanded rockfish	94	35.6
Painted greenling	28	10.6
Vermilion rockfish	27	10.2
Blackeye goby	20	7.6
Copper rockfish	10	3.8
Olive rockfish	7	2.7
Pile perch	7	2.7
Brown rockfish	6	2.3
Squarespot rockfish	6	2.3
Stripefin ronquil	6	2.3
Flag rockfish	5	1.9
Kelp rockfish	4	1.5
Cabazon	3	1.1
Blue rockfish	2	0.8
Lingcod	2	0.8
Northern ronquil	2	0.8
<i>Sebastomus</i> sp.	1	0.4
Stripetail rockfish	1	0.4
Treefish	1	0.4
Unidentified fish	1	0.4
Unidentified ronquil	1	0.4
Minimum Number of Species	20	
Total Number	1,199	
Percent Rockfishes	94.7%	
Total Density		454.9

Holly and the seep tents may each be seen as having two loosely connected habitats, the mid-waters and the bases, although these bases function in slightly different ways.

Three-dimensional habitat complexity (e.g., surface rugosity, microhabitat density, crevice intensity, height, diversity of structural shapes, macroalgae), regardless of habitat composition, has a substantial influence on both marine and freshwater fish species assemblages worldwide (Ferreira et al. 2001; Gratwicke and Speight 2005; Dauwalter and Fesenmyer 2017; Ferrari et al. 2018; Eggertsen et al. 2020; Hall and Kingsford 2021). In reference to coral reefs, but likely also applicable to temperate regions, “Habitat complexity is a determinant of reef fish assemblages, where fish abundance, biomass, and richness are often positively correlated with complexity” (Asner et al. 2021). Perhaps predictably, a reduction in reef complexity can lead to “reduced abundance and diversity of reef fishes” (Graham 2014). It is becoming increasingly clear that, specifically in regard to offshore platforms and their associated structures, their shape, height and complexity can also strongly influence this composition (Bond et al. 2018; McLean et al. 2019; Love et al. 2019b; Birt et al. 2024).

However, in addition, and at least off California, a specific type of habitat complexity influences not only fish species assemblages, but also the sizes (i.e., maturation stages) of a number of species. In this instance, there are a suite of species, that we have previously termed the

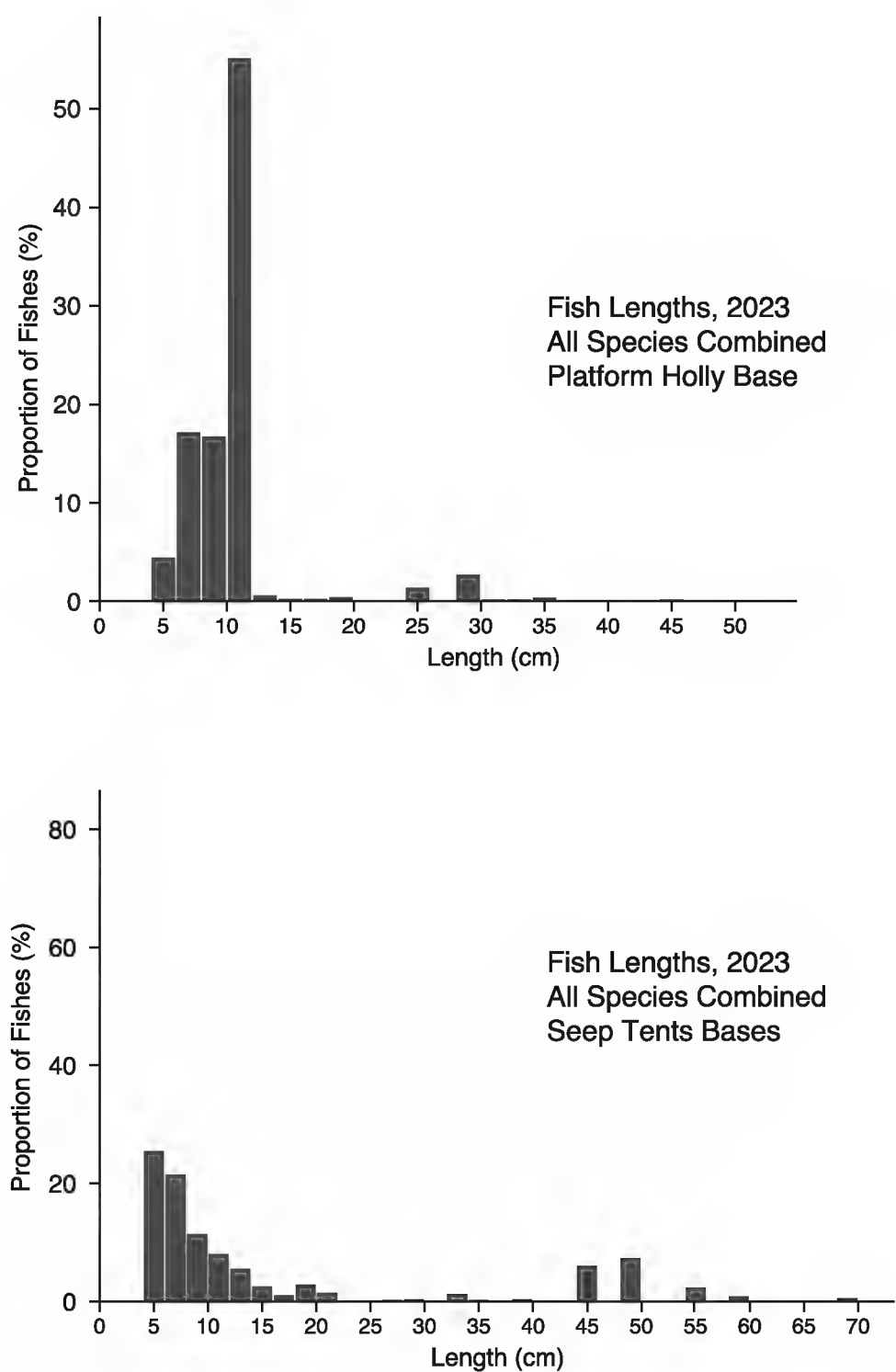


Fig. 6. Size structure of all fishes observed at the base of Platform Holly and the bases of the seep tents, based on ROV surveys conducted in August 2023. Holly base, N = 1,199, tent bases, N = 781.

“sheltering complex,” whose adults are almost always found in association with caves and crevices around natural habitat, or among the equivalent on human-made structures (Love and York 2006; Love et al. 2006). For these species, including copper rockfish and vermilion rockfish, the platform midwaters, base, and seep tent towers, although composed of hard structure, lack the requisite sheltering sites. However, this is not the case with the seep tents bases, where shelves and various openings create a very specific subhabitats.

It is likely that the YOY fishes observed at all four habitats were derived from planktonic larvae or pelagic juveniles (as opposed to being derived from fish that recruited elsewhere and swam to these habitats) as the very small size of these fishes correlates to the lengths these fishes are known to recruit from the plankton. The YOYs of at least three species, the viviparous pile perch, sharp-nose seaperch, and white seaperch (although rarely observed in this study), most probably were derived from adults that gave birth at the platform, as it is unlikely that, at this early life stage, these small, and reef-dependent, fishes could have swum to the platform over soft sea floor from

Table 4. Fish species observed at the two seep tent towers combined, based on ROV surveys conducted in August 2023. YOY refers to young-of-the-year unidentifiable below the genus level. Fishes are listed by densities (individuals 100 m⁻²). Scientific names are given in Table 1.

Species	Number	Density
YOY rockfish	145	396.6
Kelp rockfish	13	35.6
Blue rockfish	5	13.7
Vermilion rockfish	3	8.2
Brown rockfish	2	5.5
Copper rockfish	2	5.5
Rosy rockfish	2	5.5
Widow rockfish	2	5.5
Cabazon	1	2.7
Painted greenling	1	2.7
Minimum Number of Species	9	
Total Number	176	
Percent Rockfishes	98.9%	
Total Density		481.5

other reefs. Vermilion rockfish recruit to shallow, nearshore waters and within a few months migrate into somewhat deeper waters. As we did not observe newly recruited vermilion rockfish, the juveniles that inhabited the platform base had probably recruited from shallower waters. The occurrence of primarily juvenile bocaccio, copper rockfish, lingcod, and vermilion rockfishes in the platform midwaters and at the platform base, and adults of these species at the seep tents bases, suggests that the platform acts as a nursery ground for these species, which may then migrate to the seep tent bases as their habitat requirements change with maturity.

We note that this study only encompassed a single survey during one year. However, regarding the fish assemblages and their size structures, we believe the patterns we observed in that year are of long standing. We have conducted a number of fish surveys around Platform Holly, using a human-occupied research submersible, beginning in 1995 and ending in 2011¹. These demonstrated that the dominant species assemblages in the midwaters and around the base, and their size frequencies, did not change over time. And while, until 2023, we did not conduct any formal seep tent surveys, we have reviewed industry-based inspection videos conducted during the 2010s, and did observe the same patterns in those surveys as we observed in 2023.

Augmentation.—How might these observations effect the two platform decommissioning options? On the basis of this and previous platform surveys, and based on previous research on the ecology of mesophotic reef fishes in southern California (Love et al. 2006, 2009, 2019a,b), if complex material (e.g., quarry rock or part of the removed jacket) were added to the base of Platform Holly, whose jacket had been removed to a depth of 26 m, the overall platform fish assemblage would likely resemble that of the seep tents and that of rugose natural reefs. That is:

- 1) Additional complexity to the platform base would likely not change the midwater assemblage, and it would remain the domain of YOY and older juvenile fishes (primarily of rockfishes but also, among others, cabazon, and painted greenling), as well as relatively low densities of such reef-oriented species as kelp rockfish, gopher rockfish,

¹ Data are available at https://drive.google.com/file/d/1Ulr7ON5R-BG5oyzfSJEnss0DBJu8ok5w/view?usp=drive_link

Table 5. Fish species observed at the two seep tent bases combined, based on ROV surveys conducted in August 2023. YOY refers top young-of-the-year unidentifiable below the genus level. Fishes are listed by densities (individuals 100 m⁻²). Scientific names are given in Table 1.

Species	Number	Density
YOY rockfish	332	30.5
Vermilion rockfish	89	8.2
Pink seaperch	74	6.8
Calico rockfish	63	5.8
Halfbanded rockfish	63	5.8
Copper rockfish	27	2.5
Rosy rockfish	23	2.1
Blackeye goby	22	2.0
Brown rockfish	18	1.7
Squarespot rockfish	14	1.3
Blue rockfish	13	1.2
Painted greenling	11	1.0
Unidentified fishes	8	0.7
Bocaccio	3	0.3
Cabazon	3	0.3
Lingcod	2	0.2
Longspine combfish	2	0.2
Pile perch	2	0.2
Shortbelly rockfish	2	0.2
Unidentified ronquil	2	0.2
Widow rockfish	2	0.2
Flag rockfish	1	0.1
Cowcod	1	0.1
Gopher rockfish	1	0.1
Shortspine combfish	1	0.1
Stripetail rockfish	1	0.1
Unidentified sanddab	1	0.1
Minimum Number of Species	24	
Total Number	781	
Percent Rockfishes	83.6%	
Total Density		72.0

and sea perches. In particular, we speculate that the rockfish nursery function of the platform midwaters would not be substantially impinged upon. We base this on several lines of research and among these are: A) Claisse et al. (2015) found that at California platforms most fish biomass and secondary productivity occurred below the cut-off

Table 6. Games-Howell Post-hoc test results for fish size differences across four different habitats. This test was conducted following Welch’s ANOVA. It displays the mean differences in fish sizes between habitat pairs, the adjusted p-values, confidence intervals, and whether the differences were statistically significant (asterisk indicated significant pairs).

Group 1	Group 2	Estimate	Conf.Low	Conf.High	P Value	Signif.
Platform Base	Platform Midwater	−3.14	−3.55	−2.72	<0.01	*
Platform Base	Seep Tents Bases	5.98	4.41	7.56	<0.01	*
Platform Base	Seep Tents Towers	0.501	−1.73	2.73	0.937	
Platform Midwater	Seep Tents Bases	9.12	7.58	10.7	<0.01	*
Platform Midwater	Seep Tents Towers	3.64	1.43	5.84	<0.01	*
Seep Tents Bases	Seep Tents Towers	−5.48	−8.15	−2.81	<0.01	*

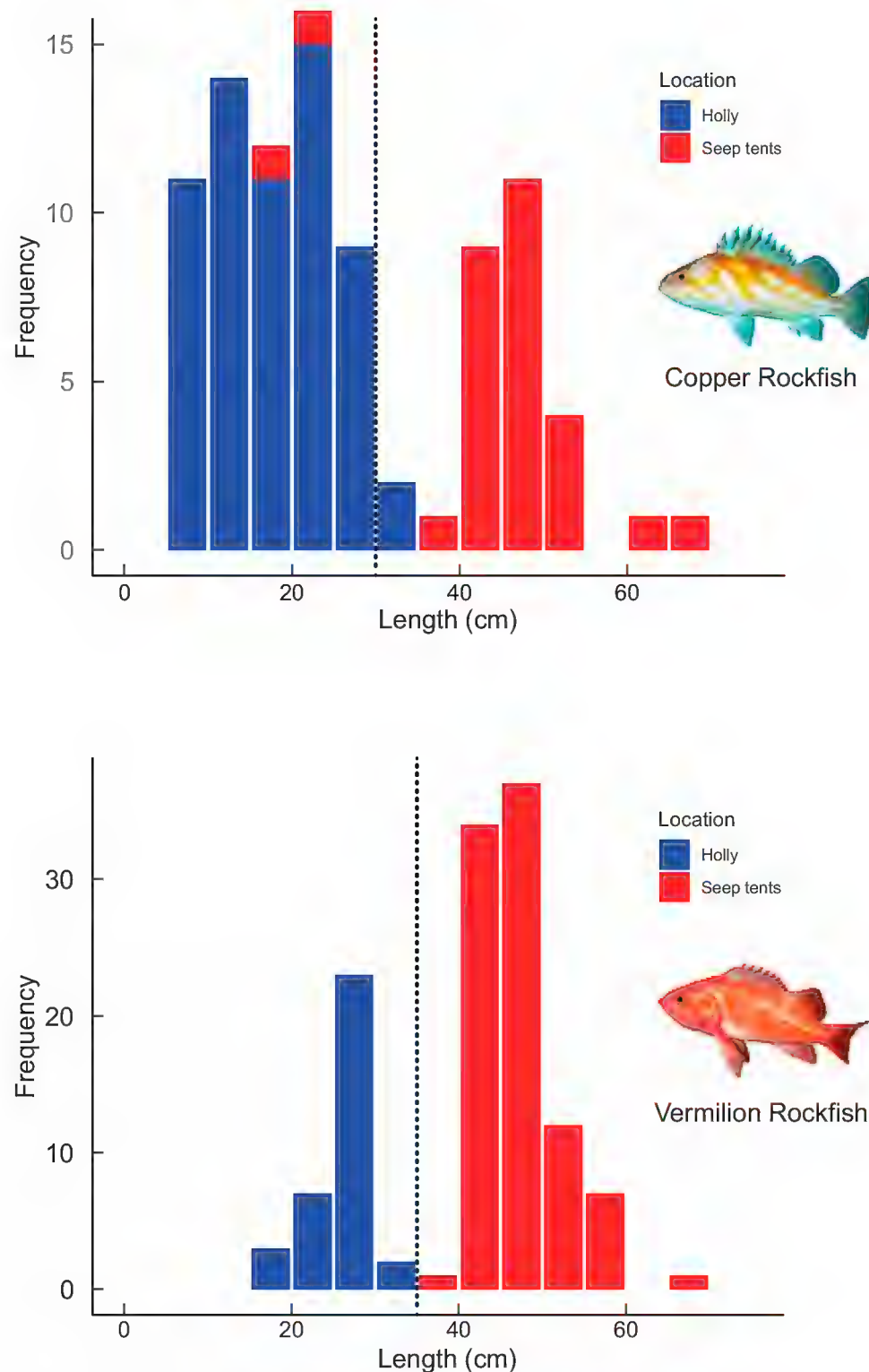


Fig. 7. Size frequencies of two economically important rockfishes (copper rockfish and vermilion rockfish) at the base of Holly and the bases of the seep tents, based on ROV surveys conducted in August 2023. Dashed vertical lines represent sizes at 50% maturity. Frequency = numbers of individuals.

depth of 26 m. B) Love et al. (2012), conducting surveys on surrogates for topped platforms, concluded that removing the top 26 m of a platform would decrease blacksmith recruitment, but have little effect on rockfish recruitment. C) YOY rockfish recruitment was quite robust around the seep tents towers, even though these towers peaked at a depth of 51 m, a depth much greater than the hypothesized topping depth.

- 2) The base of Platform Holly would, importantly, likely now harbor mature fishes of those larger species, such as bocaccio, brown, copper, and vermilion rockfishes, and lingcod, usually associated with shelter-rich habitats. We might also expect that there would be an increase in the densities of YOY rockfishes, over that of the unaltered (original) base, at least similar to that at the seep tents bases, and to that of complex, high-relief natural reefs (e.g., Love et al. 2022).

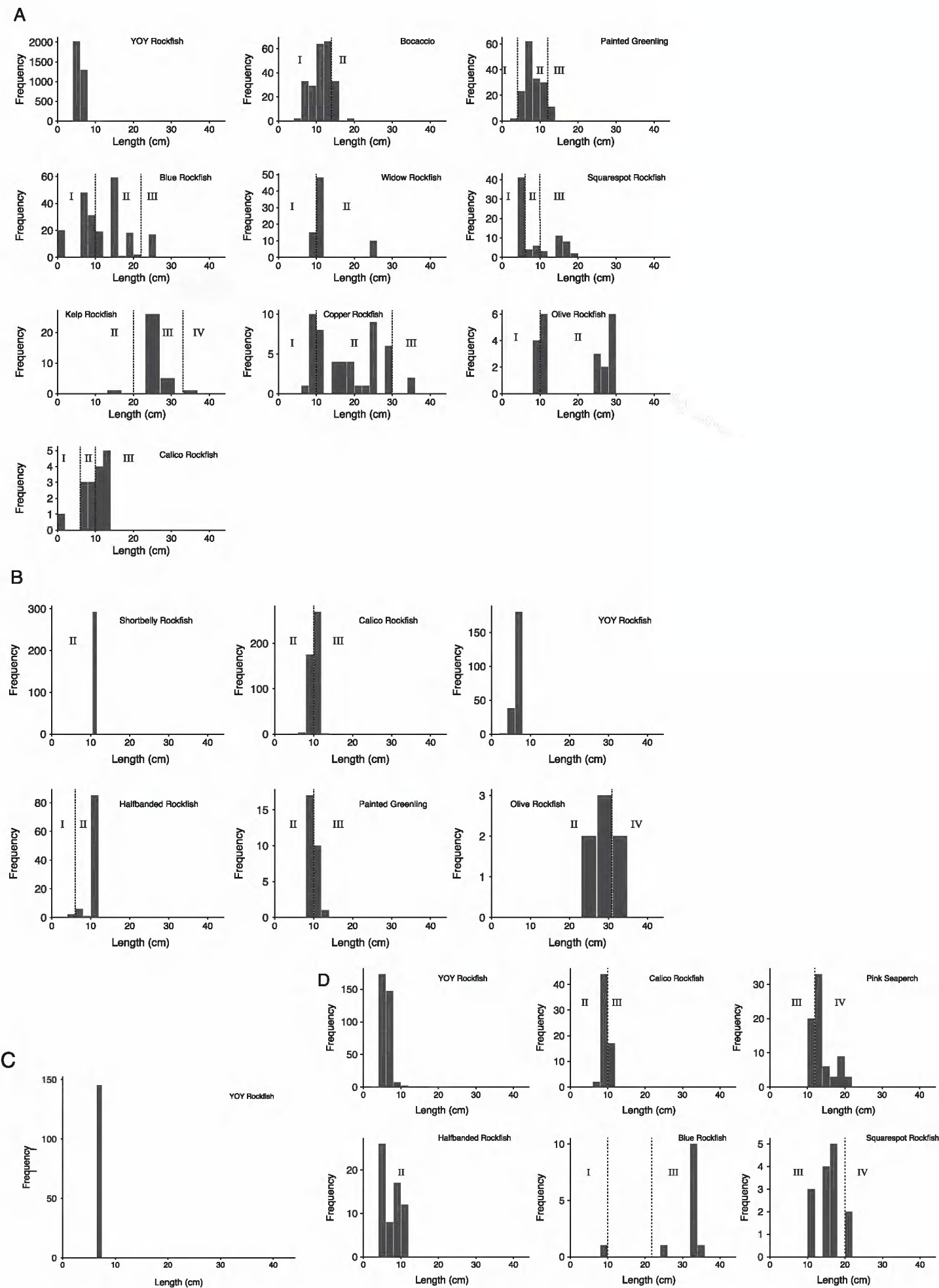


Fig. 8. Size frequencies of some of the more important species or species groups found around Platform Holly and the two seep tents, based on ROV surveys, 2023. I = likely YOYs, II = likely older juveniles, III = likely older juveniles and some adults, IV = adults. A) all crossbeams combined, B) platform base, C) seep tents towers, and D) seep tents bases. Note that size frequencies of copper rockfish and vermilion rockfish, for the platform base and seep tents bases, are shown in Fig. 7. Frequency = number of individuals.

- 3) At the fringes of this new benthic habitat, and over the remnants of the shell mound, would likely be found the juvenile stages of the previously mentioned species, as well as mature individuals of taxa previously found at the base, such as calico rockfish, pink seaperch, painted greenling, blackeye goby, and stripefin ronquil.

We acknowledge that such sea floor habitat alteration brings with it some potential issues. In particular, if there is no complex habitat nearby (although not the case with Platform Holly), such augmentation raises the possibility of introducing fauna not specific to the immediate area. And whether any alteration from the natural fauna is “beneficial” is not so much a scientific question, rather it is philosophical one.

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